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GEOPHYSICAL METHODS APPLIED TO OIL PROSPECTING.

By J. McGarva Bruckshaw.

Editorial Note.—*With the greatly broadened scope of membership and the change in character of the Institute of Petroleum, the Council has felt the time ripe to undertake the preparation of a work under the title of "Modern Petroleum Technology" which shall present to its readers a composite picture of the present state of petroleum technology.*

The aim of this series of articles is that they will be primarily of general interest to all classes of members of the Institute and, although not popular in the generally accepted sense of the word, that they shall convey the knowledge of the specialist in an intelligent and educative manner to his less specialized confreres in the industry.

While the proposal is to publish the series in the form of a manual of petroleum technology, it is hoped that the articles will first be published, as received, in the Journal.

During the last thirty years a new tool has been placed in the hands of prospectors for mineral deposits, in the form of the recently developed methods in which physics has been applied to geological problems. These methods make use of a difference in some physical property of the mineral sought and the surrounding rocks, with the provision that the physical property must be capable of influencing a physical observation which can be made at the surface. This last condition limits the number of properties which can be usefully employed in this work, and the four which have been exploited most are the rock densities, their elastic properties combined with their densities, their magnetic properties, and finally their electrical conductivities. These four properties lead to the four well-established groups of prospecting, the gravitational methods, the seismic methods, the magnetic methods, and the electrical methods.

In some cases the deposit itself provides the contrast in the physical properties, but in many cases the search is indirect, since the mineral has no outstanding physical characteristics. Oil is a case in point, since an oil-bearing formation, as a rule, differs little from the neighbouring rocks. The search here is for structures with which oil accumulations may be associated. Thus the gravitational method has been used to locate salt-domes, anticlines, and fault-traps, and the magnetic method to locate uplifts in an igneous basement rock, or for the location of faults by magnetic rocks which may be associated with them. The seismic method has been found useful in obtaining detail of small structures or features the gentle slopes of which render them unsuitable for gravitational work and also as a reconnaissance survey for saltdomes. In common with all geophysical surveys, it must be emphasized that the presence and nature of the deposit cannot be inferred explicitly from the observations. The methods can be used only to guide the placing of drill-sites in the most promising positions.

The Seismic Methods.

Mechanical disturbances in the ground, produced, for example, by an explosion or an impact, travel through different rocks with different velocities. In the seismic methods of prospecting use is made of this, together with the reflection and refraction of the disturbances by boundaries

between adjacent rocks, to obtain information concerning the position and form of the interface. The method was originated in 1920 by Mintrop, who suggested that the principles, which had been applied so successfully to the interpretation of earthquake phenomena, might be applied to small-scale geological problems, the natural earthquake being simulated by the detonation of a buried explosive charge.

Waves in Solid Bodies.

The explosion of a buried charge produces, in general, a complex deformation of the rocks in its vicinity, and the deformations of the rocks travel outwards from the explosion in exactly the same way as a sound-wave from an explosion in air. In a solid body at least two types of waves are produced, each travelling with its own characteristic velocity. The two types are called the *P* wave and the *S* wave, respectively. The former is a compressional wave, of a similar nature to a sound-wave, with the vibration of the rock particles backwards and forwards in the direction of propagation, while the latter is a transverse wave with the rock movement across the direction of travel of the wave. The velocities with which these elastic waves travel through the rocks depend on the elastic properties and the densities. Since different elastic properties are called into play in the two types, they travel with different velocities, and in all cases the *P* wave is the faster, and usually its velocity V_P is about $1{\cdot}7V_S$, where V_S is the velocity of the *S* wave. The magnitude of the velocities of the *P* waves for a number of rocks is given in Table I.

TABLE I.

Sandy clay . .	1200 metres/sec.	Granite . . .	7000 metres/sec.
Limestone . .	4500 ,,	Sandstone . .	3000 ,,
Rocksalt . .	5000 ,,		

In addition to these, when the explosion takes place near the free surface, a surface wave—the Rayleigh Wave—is also set up. This carries away a large fraction of the energy of the explosion, and, since it is propagated over the surface only, its intensity dies away far more slowly than that of either the *P* wave or the *S* wave, for these travel in all directions throughout the body of the rock. Thus the displacements of the ground when the Rayleigh Wave passes over it are, in general, greater than those produced by the other waves. This wave can also be recognized by its much slower velocity, which is only about nine-tenths of the velocity of the *S* wave.

Behaviour of Elastic Waves at Boundaries.

When an elastic wave is incident on a boundary between two rock media transmitting the disturbances with different velocities, it behaves in much the same way as an incident light beam on a glass surface. Part of the energy is reflected, the incident and reflected beams obeying the normal laws of reflection, and part of the energy is transmitted into the second medium with a change of direction (Fig. 1). A simple relation exists between the angle of incidence θ, the angle of refraction r, and the two velocities—*i.e.* :

$$\frac{\sin\theta}{\sin r} = \frac{V_1}{V_2}.$$

If V_2 is the greater, r will be greater than θ, and there will be a certain critical angle of incidence θ_c for which r is 90°—*i.e.*, the refracted wave travels along the boundary with the velocity V_2. For any incidence

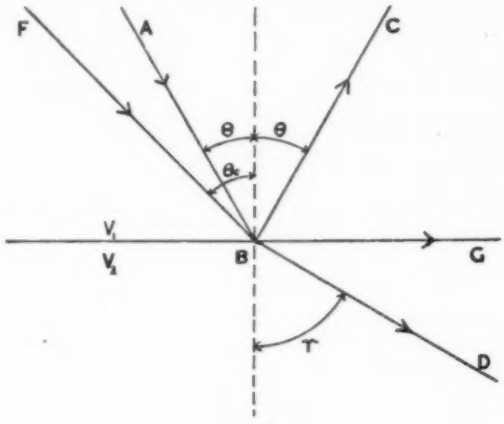

FIG. 1.

REFLECTION AND REFRACTION OF ELASTIC WAVES.

AB is the incident wave giving the reflected wave *BC* and the refracted wave *BD*. For critical incidence *FB*, the refracted wave travels along the boundary *BG*.

greater than θ_c all the incident energy is reflected, none being transmitted into the second medium. This is a simplified version of the actual events which occur, for, in general, change of type also takes place, an incident

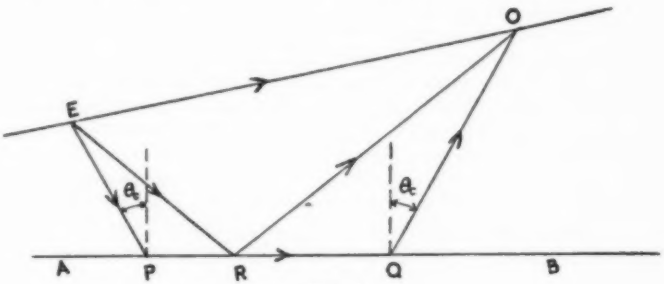

FIG. 2.

POSSIBLE PATHS FROM AN EXPLOSION AT *E* TO INSTRUMENT *O* ON THE GROUND SURFACE.

P or *S* wave giving rise to a reflected *P* wave, a reflected *S* wave, a refracted *P* wave, and a refracted *S* wave.

The motion of the ground surface can, accordingly, be extremely complicated in the presence of a boundary. First there are the three direct waves (Fig. 2), the *P* wave, the *S* wave, and the surface Rayleigh Wave

travelling from the explosion to the observation point along *EO*, and arriving at different times. To these must be added a number of reflected waves following paths such as *ERO*, since the energy can travel to the reflecting boundary as one type and be reflected as the same type or as a changed type. Refracted waves are also possible. The incident energy travels to the boundary along *EP*, meeting it at the appropriate critical angle. The refracted wave travels along the boundary *PQ*, and at all parts of its path energy is returning to the first medium and some will travel to the observation point along *QO*. Here, there are three parts of the path and each section can be covered either as a *P* or an *S* wave. The order in which these various waves arrive is not fixed, but depends on the relation of the distances involved and the velocities. The first arrivals, however, can always be associated with a wave which has travelled over all sections of its path as a *P* wave.

Detection of Ground Motion.

It would be impossible in the space available to give a detailed description of the various instruments which can be employed to detect and record the motion of the ground. Such instruments are usually called seismographs, although this term is usually used in connection with mechanical instruments, those incorporating electrical recording being referred to as geophones. They are essentially pendulums of various designs in which the inertia mass tends to remain stationary while the frame of the instrument follows the ground motion. The relative movement between mass and frame is thus a measure of the ground motion, and this relative motion suitably magnified is recorded on a moving film. In mechanical seismographs the magnification is obtained by mechanical and optical levers, while in geophones the amplification is achieved by stages of valve magnification. Instruments can be designed to record either the vertical or horizontal component of the ground motion, and the displacement, velocity or the acceleration may be selected for measurement. In addition to a record of the ground movement, two other features are included on the photographic record, a time scale, and the instant of the explosion. The time-scale is usually obtained from pendulums of known short period, or from standard tuning-forks. To obtain the instant of the explosion, an electrical circuit is broken at a wire buried in the explosive, and the resulting current change is recorded on the moving film. It should be emphasized that the present state of seismic prospecting is governed to a great extent by the design and development of these instruments, many of the applications relying on the sensitivity and selectivity which can be attained by modern instruments.

Methods of Utilizing Elastic Waves.

There are two main methods by which the elastic waves can be made to furnish information concerning the underground structure : the refraction method and the reflection method. The refraction method can be employed as a reconnaissance method for locating regions transmitting the waves with a high velocity—*i.e.*, saltdomes, to determine depths and dips of persistent horizons, or to obtain depth variations of a particular boundary. Accordingly, it is convenient to subdivide the refraction method into (*a*)

fan shooting, (*b*) traverse shooting, and (*c*) arc shooting, respectively, depending on the object of the survey. In reflection prospecting there are two main methods, the method adopted being governed by the nature of the geology examined. The first method is depth shooting, in which the depth determination is the important consideration, and the second is dip shooting, the structure of the area being revealed mainly by the variations in the dip of the reflecting horizons.

Refraction Prospecting.

(*a*) *Fan Shooting.*—If a series of seismographs are placed on an arc of a circle with the explosion point as centre, and if the ground is everywhere uniform, all instruments will receive the first arrival at the same time. When, however, one of the lines joining an instrument to the explosion point passes over a saltdome, which transmits the wave with a greater velocity, this particular instrument will be excited before the others. This is the simple theory of fan shooting. In general, it is not convenient to place all instruments at the same distance from the shot, and a modified procedure is necessary. A number of detectors are laid out on a straight line passing over normal ground, free from any velocity peculiarities, and through the explosion point. This gives a normal time-distance curve for the region. For the fan shooting, the time is plotted against distance on the same diagram, those points falling on the curve corresponding to a line passing over normal ground, and for a line passing over a saltdome or other high-velocity region the point will fall below the curve.

The saltdome at Vermilion Bay [1] was located by this method, the lay-out and time–distance curves being shown in Fig. 3. The position of the detectors for some of the shots are given in Fig. 3(*a*). In all, sixty-one shots were fired in sixteen days. The distance from the shot to the receiver was measured by the time taken for the sound-wave to travel to the instrument through air. In this method corrections have to be applied for temperature, humidity, wind velocity, etc., but it is claimed that over water errors are less than 200 ft. in a distance of five miles. In Fig. 3(*b*) the smooth curve gives the normal time–distance curve for the area, and it will be seen that the majority of the observation points for the various fan lines fall about this curve. A few points, however, fall well below the curve, and the discrepancy is too great to be accounted for by experimental error. They actually correspond to lines passing over a saltdome, and a number of overlapping fans gave its exact location.

(*b*) *Traverse Shooting.*—The main object of traverse shooting is the measurement of depths and dips of boundaries between the different rocks. In it, a series of seismographs, S_1, S_2, S_3, etc. (Fig. 4), are laid out on a straight line passing through the explosion point O, and the travel time of the first arrival at each instrument is recorded and plotted as a time–distance curve. The method is best illustrated by the simple case of a surface layer of uniform thickness H resting on a rock transmitting the shocks with a *greater* velocity. The method cannot be applied unless this condition is satisfied. The first arrival can reach the seismograph by two paths, the direct path OS_1, or by an indirect refracted path $OPQS_1$. In this the impulse from the explosion travels down to the interface, which it meets at the critical angle θ_c, and is then refracted along the

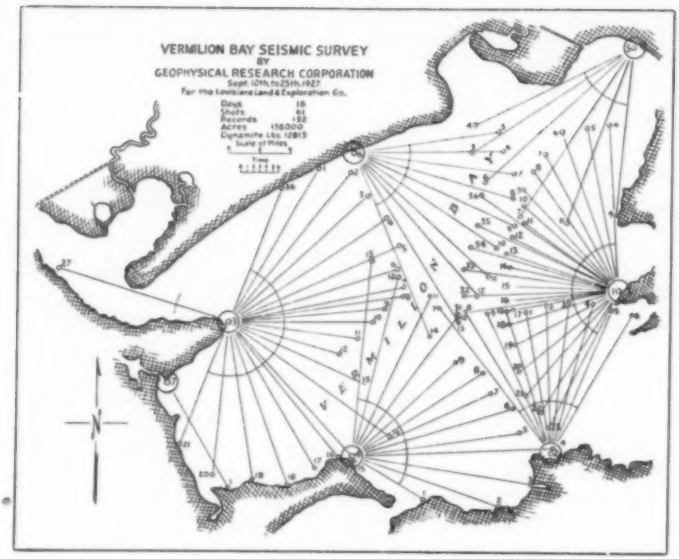

FIG. 3 (*a*).

LAY-OUT OF THE FANS AT VERMILION BAY.

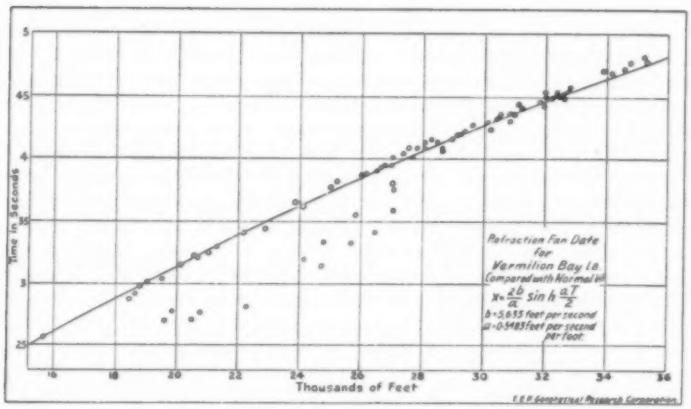
Time in Seconds
Thousands of Feet
Refraction Fan Date for Vermilion Bay La. Compared with Normal at
X= 2b/a sin h a T/2
b=5.835 feet per second
a=0.5485 feet per second per foot
E.E.P. Geophysical Research Corporation

FIG. 3 (*b*).

RESULTS PLOTTED ON THE NORMAL TIME-DISTANCE CURVE.

boundary with the greater velocity V_2. At all points along the boundary, energy will re-enter the upper layer and travel along the paths QS_1, RS_2, TS_3, etc., to the various detectors. For the direct wave, travelling with the velocity V_1 of the upper layer, the time–distance curve will be a straight line OA, the slope of which allows the velocity V_1 to be measured. For the refracted wave there is a time delay corresponding to the time taken to travel to and from the boundary. At short distances the direct wave is the first arrival, but at greater distances the delay is more than compensated by the length of the path covered with the greater velocity, and the refracted wave arrives first, corresponding to the section BC of

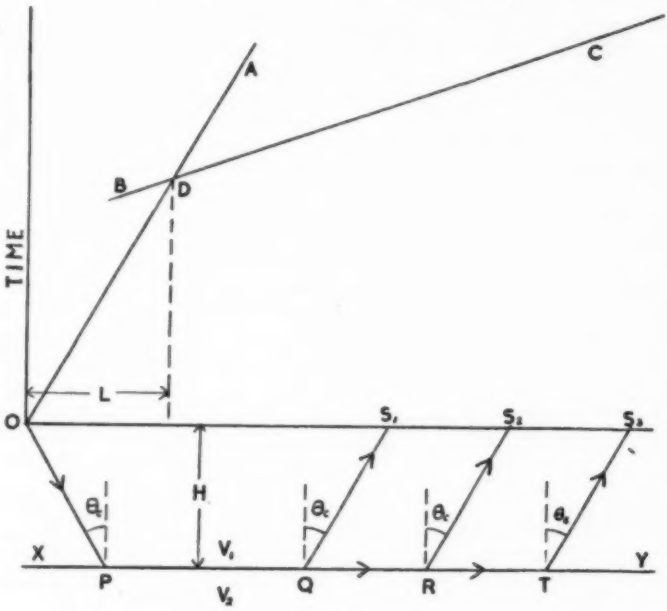

FIG. 4.

THE PRINCIPLES OF TRAVERSE SHOOTING.

the time–distance curve. This portion again is a straight line the slope of which gives the velocity V_2. This is easily appreciated, since of the paths $OPRS_2$ and $OPTS_3$, OPR is common, RS_2 and TS_3 are equal, and the time difference between S_2 and S_3 is due to the path RT along which the wave travels with the velocity V_2. The two straight lines intersect at a point where the direct and refracted waves arrive simultaneously; the delay in the refracted path is just compensated by the length of the path in the high-velocity layer. If the depth of H is small, this lag is small and only a short length of high-velocity path will be necessary to compensate for it—*i.e.*, the intersection will be close to O. On the other hand, a large delay, corresponding to a great depth, will require a long

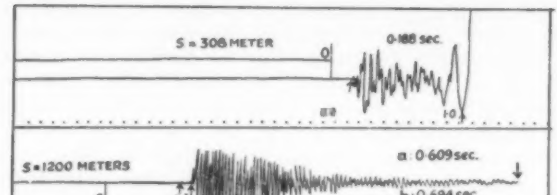

FIG. 5 (*a*).

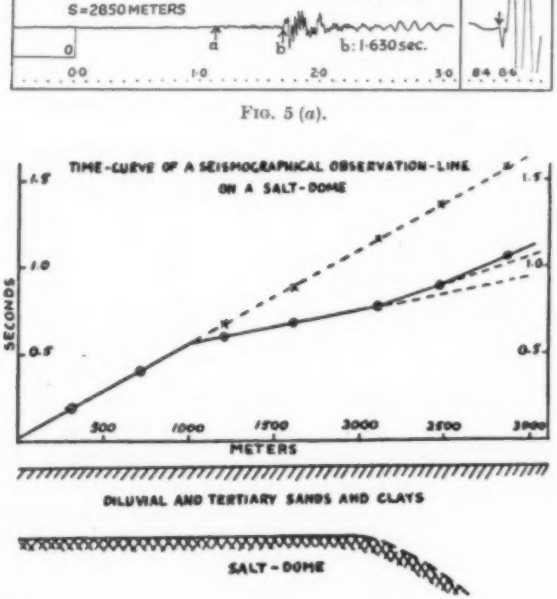

FIG. 5 (*b*).

FIG. 5 (*a* and *b*).

RECORDS AND TIME-DISTANCE CURVES OBTAINED BY SHOOTING OVER A SALT-DOME.

length of high-velocity path. Accordingly, the distance of the intersection D from the explosion is related to the depth, and it can be shown that in the above simple case

$$H = \frac{L}{2}\sqrt{\frac{V_2 - V_1}{V_2 + V_1}}$$

when L is the distance of the intersection from O.

These principles are well illustrated by Fig. 5, which shows the seismograph records and the time–distance curve for a survey over a saltdome covered by sands and clays.[2] Examination of the records (Fig. 5(*a*)) reveals that in all cases a strong arrival is present, corresponding to the direct surface wave. At short distances this is the only event, but at larger distances it is preceded by a weaker pulse, the refracted wave. The time–distance curve consists of two straight lines which give a surface velocity of about 1850 m./sec. and an underlying velocity of 4900 m./sec. From the position of the intersection, the depth of the top of the saltdome is about 350 m. At large distances the time–distance curve departs from the two straight lines, since the structure does not conform to that shown in Fig. 4.

These principles can be extended to a series of layers, as long as the velocity of each bed is greater than the velocities of the beds above it. In this case the time–distance curve becomes a number of straight lines the slopes of which give the velocities in the various beds, and from the positions of their intersections the depths of the refracting surfaces can be calculated. In addition, sloping boundaries can be examined. Once again the time–distance curve consists of two straight lines OA, BC for an explosion at O (Fig. 6). The slope of the refracted portion (BC), however, no longer gives the velocity V_2, for an inspection of the two paths $OPQS_1$ and $OPRS_2$ shows that the latter has a much shorter emergent path RS_2. Accordingly, shooting up the slope leads to the shorter times than for the corresponding horizontal boundary, and the apparent velocity of the line BC is greater than V_2. On shooting down the slope the opposite is true, the apparent velocity being less than V_2. This obviously gives a method of testing the case of a dipping boundary. Another test is to move the position of the explosion, when the distance of the intersection of the two parts of the time–distance curve will change, its distance from the explosion point increasing as the explosion is moved down the slope. Of these two methods, the former is preferable, since the additional information allows the true value of the velocity V_2, and the dip, to be calculated from the apparent velocities up and down the slope. Knowing these, the depth of the boundary below either shot points can be computed. When sloping boundaries are involved, other conditions have to be satisfied in addition to $V_2 > V_1$. The dip, added to the critical angle, must be less than 90° for the critical path to be possible. When shooting up the slope, it is possible to have conditions where the apparent velocity for the refracted wave is infinite or negative. Such features immediately point to a sloping boundary.

(*c*) *Arc Shooting.*—In arc shooting,[3] the variations in depth below the surface of some particular boundary are investigated, as distinct from the measurement of the total depth. The surface arrangement is similar

to that used in fan shooting, the explosion point being the centre of a circular arc on which the seismographs are placed. The distance from the shot-point to the various detectors is so chosen that the refracted wave is the first arrival. As in traverse shooting, the path from shot to receiver (Fig. 7(*a*)) is divided into three parts : (1) from the shot point down to the refracting boundary, (2) the path in the high-velocity medium, and (3) the emergent path from the refracting boundary to the detector. If the surface relief of the boundary is mild, the first part of this path will be approximately the same for all the receivers. Again, under the same

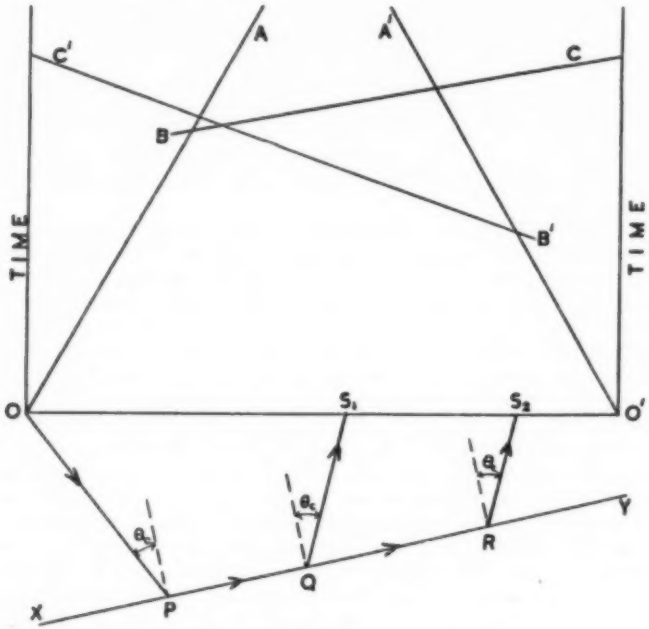

FIG. 6.

SHOOTING OVER A SLOPING BOUNDARY.

conditions, the lengths of path in the lower medium will also be roughly equal. Accordingly, the elastic pulses leave the refracting boundary on their way to the different seismographs at the same time. Thus, any time difference in their arrival can be associated with differences in the length of the emergent path. In fact, it can be shown that, for small angles of dip, the time t taken by the wave is

$$t = K + \frac{R}{V_2} + kH$$

when K is a constant depending on the depth below the shot point, R the distance from shot to detector, H the depth below the receiver and k a

constant depending on the velocities V_1 and V_2. Thus, variations in t arise only from variations in H, equal changes in the former correspond to equal changes in depth. If the various velocities are known, the value of k can be calculated and the time variations converted into feet if necessary. Alternatively, if the arrival times are plotted on a suitable scale with increasing time vertically downward, against position, the curve so obtained should reveal the section of the boundary. Fig. 7(*b*) is a diagram

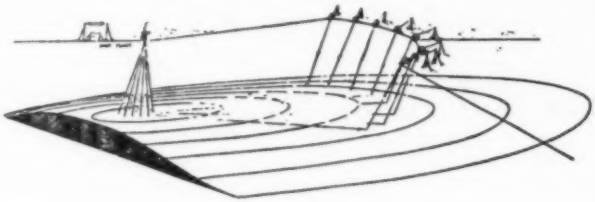

FIG. 7 (*a*).

THE PRINCIPLE OF ARC SHOOTING.

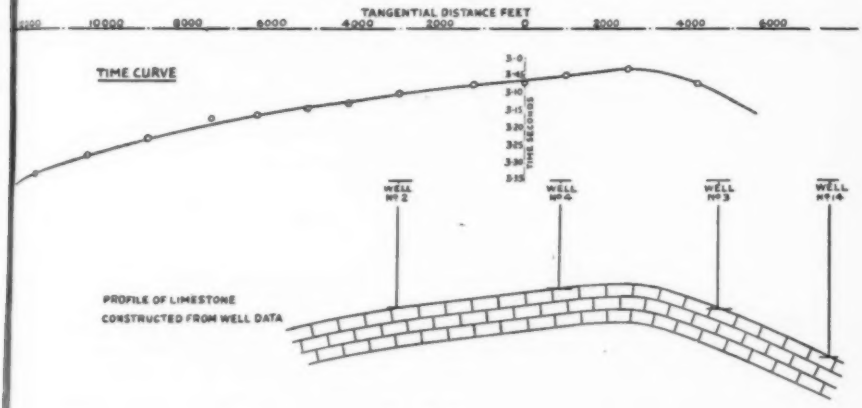

FIG. 7 (*b*).

COMPARISON OF ARC SHOOTING RESULTS AND THE KNOWN STRUCTURE.

of this nature in which the shape, revealed by the arrival times, is compared with the actual section of the refracting limestone boundary known from borings.

Reflection Shooting.

If the sequence of arrivals at an observation station are considered, it is obvious that a reflected arrival can never be a first arrival, and when the reflection arises from a deep-seated boundary, it will excite the seismograph after all the surface waves. Now, the intensity of a P wave falls off inversely as the square of the distance travelled, and only a small fraction of the incident energy is reflected. The reflected pulse is feeble in com-

parison with the Rayleigh Wave, which carries a large fraction of the explosive energy, travels a short distance along the surface to the detector, and the intensity of which falls away only as the inverse of the distance. The problems to be solved are how to detect the weak pulse against the large background, and how to identify the arrival as a reflected pulse.

It is found by experience that the frequency of the reflected pulse differs from the frequency of the Rayleigh Wave, or ground roll. Any pulse can be split into a spectrum of different frequencies, and some of these frequencies are transmitted through the rocks with less energy loss than others. For the reflected pulse, the energy is found within a frequency range of 40–60 cycles per second, but for the Rayleigh Wave much lower frequencies predominate, usually from 20 to 30 cycles per second. Electrical geophones are universally employed in reflection work, and their output consists of a current varying in sympathy with the ground motion. These currents are passed through an electrical filter circuit, which has the property of suppressing the low frequencies and transmitting the higher frequencies.

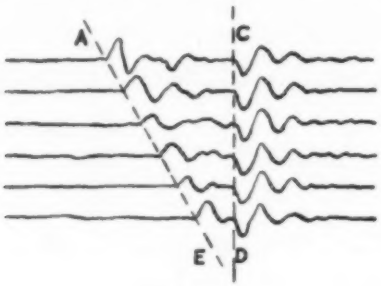

FIG. 8.

THE IDENTIFICATION OF A REFLECTED ARRIVAL.

The record obtained is thus a very distorted version of the ground motion, in which the wanted reflected pulse stands out against a reduced background.

To identify the pulse as a reflection, the arrival direction is utilized, in general this direction for a deep-seated reflecting boundary being nearly perpendicular to the ground surface. A series of geophones are laid out at equal intervals on a straight line passing through the explosion point, the distances involved being from 300 to 1000 ft. The instruments are joined up to a central recording station, where all records are made side by side on the same film (Fig. 8), the various traces across the film corresponding to increasing geophone distance. For a direct wave, or refracted wave, the geophones will be excited in succession at equal time intervals, and a line *AE* joining the arrivals on the record will be a straight line crossing the film at an angle. The reflected pulse, however, arriving vertically from below, will excite all instruments at the same instant, and if the geophones are matched, identical records will be obtained on all traces. In this case the line *CD* joining the onsets cuts the film at right angles. If, as is usual, the arrival direction is not vertical, the onsets are not simultaneous, but in very rapid succession. The time difference

between the first and last onset of the same event at the geophones is known as the " step-out " of the reflection. The record therefore yields the time taken for the reflected pulse to travel down to the boundary and back, and the " step-out ".

Before these time measurements can be used for depth determinations, the velocity along the path must be obtained. So far, the velocity in any medium has been considered constant, but in general it is found to increase with depth. When this is the case, the time–distance curve obtained from traverse shooting is a smooth curve, concave to the distance axis, instead of a straight line (see Fig. 3(*b*)), and from it the velocity at various depths

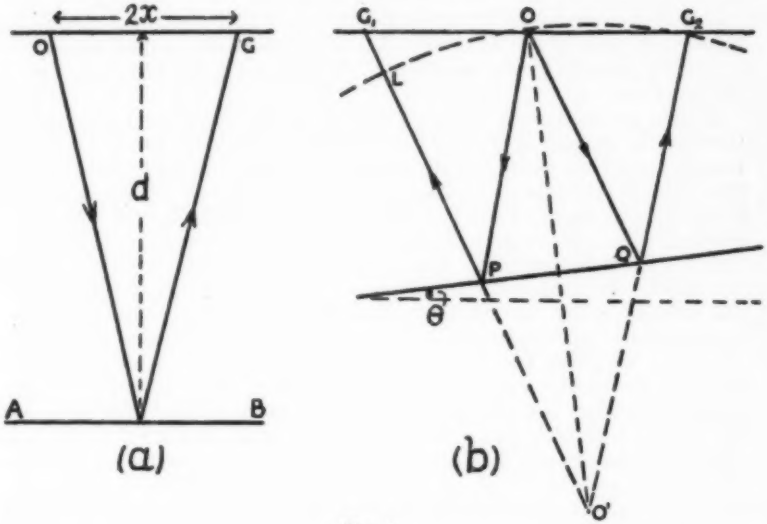

FIG. 9.

(*a*) ILLUSTRATING THE DEPTH CALCULATION. (*b*) THE PRINCIPLE OF DIP MEASUREMENTS.

can be calculated. Sometimes it is possible to make direct velocity determinations by well-shooting. In this, a geophone is lowered to various depths down a well, and the time observed for a pulse to travel from a surface explosion to the geophone. By these, and other methods, the velocity along the path of the reflected wave can be computed and the depth of the reflecting horizon obtained. For a uniform velocity V and an arrival time t, the depth of the reflecting surface AB (Fig. 9(*a*)) is given by

$$d^2 = \frac{V^2t^2}{4} - x^2$$

where $2x$ is the distance between explosion and geophone. Since x is usually small in comparison with d, this may be replaced by $d = \frac{Vt}{2}$. Many records show an abnormal " step-out " (Δt) for the depth obtained,

and this has been rightly attributed to a dipping boundary, large step-outs corresponding to shooting down dip, and small values to up dip shooting. The step-out can be used to estimate the dip, and the principle is illustrated in Fig. 9(*b*), in which the geophones G_1, G_2 are placed symmetrically on each side of the explosion point O. For a surface layout of this nature, and a horizontal reflecting boundary, both geophones would be excited at the same instant. With the sloping boundary, G_1 is excited after G_2 by an amount corresponding to the path length G_1L, which is obviously related to the dip. In this case the angle of dip θ is given by

$$\theta = \frac{d}{x} \cdot \frac{\Delta t}{t}.$$

In general, Δt is of the order of a few hundredths of a second only, and cannot be measured very accurately. Thus the dip is known only to a degree or so.

Certain corrections have to be applied to the observed times before they can be used for depth and dip estimates. These are usually grouped together under the heading of the surface correction. It takes into account the surface elevations at the shot point and geophone, the depth of the shot, and the depth of the geophone, which is usually buried below the surface. The most important part, however, is the correction for the so-called " weathered zone ". This is a surface layer which transmits the waves with an abnormally low velocity, frequently less than a quarter of the velocity of the rocks below. Its existence has been appreciated for a long time, but the reason for the low velocity has not been completely explained, although Lester [4] has suggested the presence of air within the rocks as the cause. The zone does not conform with the region of the weathered rocks, and the choice of name is unfortunate. Its thickness may vary considerably over the reflection layout, and it is for this reason that the correction is so important. No additional experiment is necessary, the first arrivals at the geophones, when interpreted on the lines already indicated for refraction shooting, allowing the depth changes to be obtained.

(*a*) *Depth Shooting*.—The necessary conditions for satisfactory depth shooting are : (i) that there should exist in the region a contact between two media which acts as a good reflector, (ii) the contact should conform to the structure to be investigated, and finally (iii) the contact should persist throughout the whole area to be examined. In these circumstances there is on each record a strong arrival which corresponds to a reflection at the boundary in question, and the arrival can be correlated with similar arrivals on all other records. Depth and dip determinations are made at each station, and the results plotted on a section. By joining the depth points so obtained, a profile of the structure is developed and, if necessary, contours of the contact can be constructed. This procedure has been found satisfactory, for instance, in Oklahoma, where shales overlie Mississippi and Ordovician limestones, the contact between them serving as a good reflecting horizon.

As an example of this type of survey, one described by McDermott [5] may be considered. It was carried out in the Eastern Navarro and Western Henderson Counties of Texas, in a region where sands and shales rest on Pecan Gap chalk, which in turn lies on Austin chalk. The work consisted

of measuring the depth of the top of the Pecan Gap chalk and of a basal member of the Austin chalk. The upper sections of the Austin chalk did not give consistent reflections. Two shots were used at each station, a small one yielding a reflection from the upper reflecting horizon, but giving insufficient energy to allow the pulse from the lower horizon to be detected. The latter was observed by the detonation of the second and larger charge. Part of the results are shown as a section in Fig. 10. At station Nos. 55, 56, 57, and 59 normal records for the district were obtained, but at station Nos. 58 and 210 peculiarities were observed which confirmed the presence of the faults. At station No. 58 no reflection from the Pecan Gap chalk was obtained, but the strongest reflection from the Austin chalk was observed. On the other hand, at station No. 210, no matter how large the

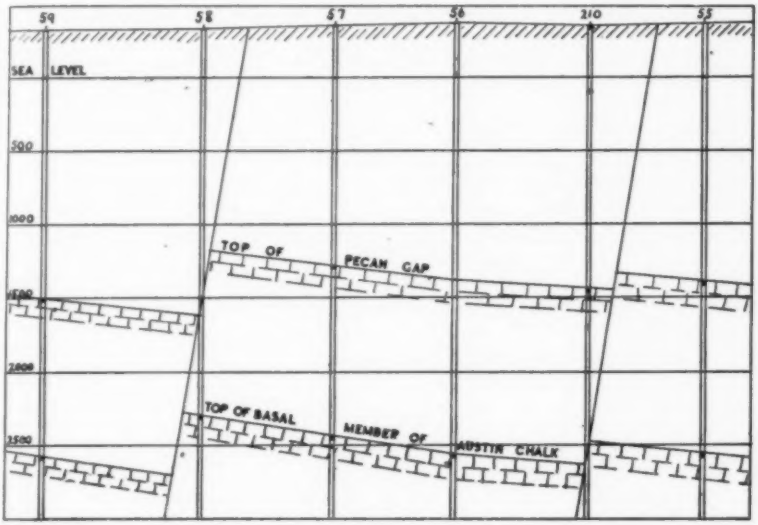

FIG. 10.

AN EXAMPLE OF DEPTH SHOOTING.

charge employed, no response could be obtained from the lower boundary, and the small charge gave a normal reflection from the Pecan Gap chalk. In all, seventy-five depths were measured in a period of two weeks, the cost working out at less than 10 cents per acre.

(*b*) *Dip Shooting.*—A more difficult problem presents itself in the Texas–Louisiana Gulf coast of America, where structures occur without persistent reflecting horizons. These conditions exist in certain sedimentary structures where a series of beds provides a number of surfaces giving similar reflected energies. Accordingly, the records are characterized by a sequence of reflected pulses of roughly the same intensity, rendering it impossible to select from each record the pulse from the same horizon. In addition, the individual beds themselves are often of small horizontal extent, thinning

out laterally and being replaced by other beds of somewhat different character. This feature tends further to confuse any attempt at correlating arrivals. Consequently, if a series of depth measurements are plotted, as in the case of depth shooting, the resulting picture reveals a number of points apparently distributed at random, from which no conclusions can be reached concerning the general structure. If, however, the dip at each reflecting surface is determined, and through each plotted point a short line is drawn with the appropriate angle of dip, the shape of the structure immediately becomes apparent. An example of this type of survey is shown in Fig. 11, which gives a typical profile in the Texas–Louisiana Gulf Coast area.[6] The dip at each depth determination is shown by the short lines, and the general structure derived from the measurements is indicated by the dotted curve. In many cases the results reveal a series of disconnected reflecting boundaries, together with one or more horizons

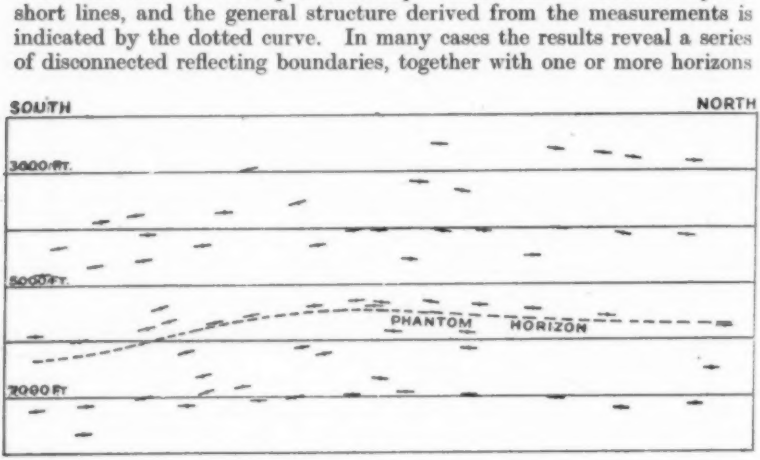

FIG. 11.

THE RESULTS OF DIP SHOOTING.

which are detected over the whole of the region. In this case depth shooting might be used, but the dips assist materially in the identification and correlation of the reflecting boundaries.

Limitations of Seismic Methods.

In general, the limitations of a geophysical method can be divided into two parts : those due to the instruments, and those arising from geological considerations. In refraction prospecting there is a definite limit to the depths which can be investigated, since the great distances involved means that ultimately the arriving signal will be too weak to be detected. In addition to this, the changing conditions over long traverses may render the interpretation obscure. The signal from the explosion must always be greater than the general ground unrest (microseisms) which form a background against which it must be picked out. To improve the ratio of signal to background, a greater charge of explosive must be employed. A similar problem arises in reflection prospecting, since the reflected arrival must be detected against the background of other arrivals also arising

from the explosion. Here, to improve conditions, the instrument selectivity must be improved.

The refraction method of prospecting has a number of disadvantages; in particular, since the distance between explosion and seismograph may be many miles, only an average section of the structure is obtained. In addition, the horizontal extent of the structure must be large, small features being unsuitable for the method. A severe restriction is also imposed by the velocity relation which has to be satisfied. Further, there are possible combinations of velocities and boundary depths in the multilayer case for which certain of the refracting boundaries will not be revealed by the use of first arrivals only. In the case of dipping strata, the angle of dip must be less than a certain value, fixed by the appropriate critical angle, before any refracted ray can emerge to the surface. Accordingly, the method is unsuitable for steep dips.

Many of these objections are overcome by the reflection technique, for, theoretically, all abrupt velocity or density discontinuities give rise to a reflection of energy. If the detector and explosion are close together, the reflected pulse travels down to the boundary and back, so that, to a first approximation, the depth at a point is measured, thus allowing smaller structures to be examined. Against these advantages there is the objection that no information is obtained concerning the nature of the rocks beyond the reflecting boundary. There is also the possibility of missing a reflecting horizon, for if the path distances between pulses from two boundaries differ by a wave-length of the reflected pulse, one will be superimposed on the other, and the lower boundary will not be detected. On the other hand, if the path difference is half a wave-length, the two will interfere destructively, and neither reflecting horizon will be detected.

The accuracy of the interpretation depends on a number of features; in particular, a knowledge of the wave velocity, which, in general, will vary along the path. The exact determination of this factor is difficult, and calculations are usually based on the assumption that the velocity varies with depth only. It is obvious that in the vicinity of anticlines, etc., where the results are most important, this assumption is not justified, for it is the depth variation of any one bed which is under examination. An important feature limiting the accuracy of dip shooting is the weathered layer, small errors in the estimation of its varying thickness leading to large errors in dip. As Rosaire and Adler point out, a difference of 3·5 ft. in the thickness of the low-velocity zone between the ends of the geophone spread may easily produce an error of about 1° in the computed angle of dip, if not properly corrected. One great advantage of the method is that the ruggedness of the surface offers no difficulty, as correctness can be applied for level differences. As with most methods, there are areas where the records show a complex character and are difficult to interpret, and it appears that the method is unsuitable for regions of large dips.

Achievements of the Seismic Methods.

Sawtelle's data show that the seismic refraction method, alone or supported by the torsion balance, played a part in the discovery of some forty

saltdomes in the Gulf Coast region of the U.S.A. during the period 1924–1930. The particular mode of application, which proved so effective for a time in this area, was fan shooting, and this served as a relatively simple method for the purpose.

In its more conventional form, the refraction method is suitable for regional studies, by its ability to determine the depth of the basement in areas with a thick cover of comparatively unconsolidated sediments, while the arc method has proved valuable, and was, indeed, designed, for locating structures in the competent Asmari Limestone beneath the highly contorted and incompetent cover of the Fars series in Iran. It has also been employed extensively in England.

The start of the second major peak in the saltdome discovery rate for the Gulf Coast of U.S.A. coincides with the introduction of the reflection seismograph. Its effectiveness in this direction may be judged from the fact that in the period 1931–1936, it played a part, alone or in conjunction with the torsion balance or the refraction method, in the discovery of nearly all the saltdomes located. It has also been responsible for the location of some deep-seated domes by detecting the arching produced by them in the overlying beds.

Correlation shooting (depth shooting) has proved most satisfactory in Oklahoma, West Texas, and Kansas, when the strata dip gently and good reflecting horizons are persistent. In Central Oklahoma, and parts of West Texas, the Oswego, Mississippi, and Viola limestones give reflections which can be used in depth mapping. Coupled with core-drilling, the reflection methods have proved an important factor in the location of oil-fields associated with the Central Kansas Uplift.

In much of California and the Gulf Coast area, lateral variations and the lenticular character of the formations preclude the use of depth shooting, and dip shooting is employed. The reflection method is satisfactory for the detailing of structures, provided that the dips are not too steep and the structure not too complexly faulted. It also offers possibilities in the location of stratigraphic traps by its indication of the convergence of reflecting horizons or dips.

Gravitational Methods.

The Gravitational Field.

The gravitational method is based fundamentally on the universal attraction which exists between all bodies, a force which is proportional to the masses of the attracting bodies and inversely proportional to the square of the distance between them. For terrestrial bodies, the forces operating are extremely small, and in the case of two equal lead spheres, each 1 metre in diameter and of mass $5\frac{1}{2}$ million grams, it is only $\frac{1}{4}$ gram weight if the spheres are just touching. When one body attains the size and mass of the earth, the attraction becomes appreciable and it is recognized as the weight of the attracted body. To specify the attractive force due to the earth, the force per unit mass is given, and this is defined as the force of gravity (g). To a first approximation this force is directed towards the centre of the earth, its direction being given by the plumb

line, and its magnitude changes with latitude from 978 dynes per gram at the equator to 983 dynes per gram at the poles.*

Surfaces which always cut the direction of the plumb line at right angles are called equipotential surfaces or level surfaces, since any mass moving along such a surface does not change its potential energy—*i.e.*, there is no component of the gravitational force operating along the surface. In the case of the earth the level surfaces have the shape of an ellipse rotated about its minor axis, this axis coinciding with the polar axis.

Returning to Newton's Law, the attraction between a fixed mass and a small volume will depend on the density of the material filling the volume; the greater the density, the greater the mass and force of attraction. It

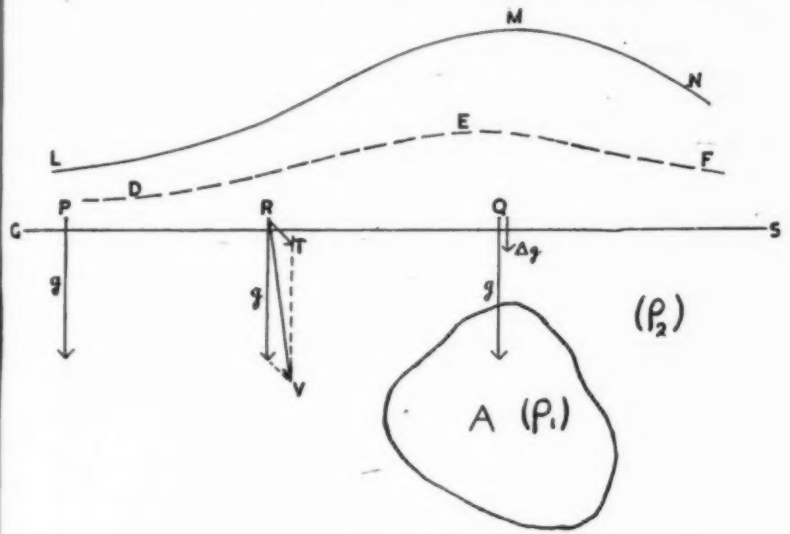

FIG. 12.

DISTORTION OF THE GRAVITATIONAL FIELD BY A BURIED DENSER BODY.

follows that local density variations in the ground will modify the force of gravity. Consider the effects of a buried body A, having a density ρ_1 greater than ρ_2 of the surrounding rocks. This distribution consists of: (*a*) a uniform density ρ_2 everywhere, together with (*b*) an excess density $(\rho_1 - \rho_2)$ in the zone A. The force acting on a unit mass at the surface consists of two parts, from these two density distributions. The former gives rise to the normal value of gravity, acting downwards through the earth's centre, this force being constant. The latter gives a force which will be directed towards the zone A (Fig. 12), and its magnitude

* The force per unit mass gives the acceleration produced, and hence the force of gravity is identical with the acceleration due to gravity, and can be measured in centimetres per second per second. In geophysics a unit of the gal. is employed where 1 gal. = 1 cm./sec.^{2}.

will decrease as the distance from the body increases. At *P*, some distance from the body, it will be negligible, and the normal force of gravity will operate. At *Q*, immediately above the body, the additional force will be appreciable, and will act in the same direction as *g*, giving a local high value of gravity. Thus gravity will increase to a maximum over the body, and then fall to its normal value on the other side, as indicated by the curve *LMN*. In addition, the plumb line is deflected, for the resultant of the two forces at *R*, given by the diagonal of the parallelogram, does not coincide with the direction of *g*. Since the level surface is perpendicular to the plumb line, it will be distorted into an anticlinal shape shown by the broken curve *DEF*. Had the zone *A* been of smaller density, a "gravity low" would occur over the body instead of a "gravity high", and the level surface would be synclinal.

The measurement of the anomalous gravity values and their interpretation is the problem confronting the geophysical prospector. Two methods are available for this purpose. The most direct method consists of measuring the force of gravity at various points, or, more usually, differences in gravity between various points. For this purpose instruments known as gravity meters are employed. In the second, and indirect, method of attack, the rate at which the force of gravity changes for horizontal displacements is measured. Between two points unit horizontal distance apart there will in general be a change in the value of gravity. If one point moves round the other, then the difference will vary, and for one position it will be a maximum. This maximum difference per unit length, in a horizontal direction, is defined as the gravity gradient, and it has associated with it a direction in which gravity is changing most rapidly. The gravity gradient can be measured by the Eötvös Torsion Balance, and with it another quantity, which depends on the curvature of the level surface, is also obtained. Historically, the torsion balance was first employed for prospecting, the development of gravity meters of sufficient sensitivity taking place only during the last few years.

Prospecting by Gravity Meter.

In a short description of this nature the instrument cannot be dealt with adequately, but it is worth while considering the sensitivity required for prospecting purposes. The general calculation of the gravity anomaly due to an irregular body is cumbersome, but some idea of the size of the anomaly associated with a given feature can be obtained by considering a buried sphere. A sphere 1000 ft. in diameter, with its centre 1000 ft. deep, will produce a gravity anomaly of 0·001 gal. (1 milligal.) immediately above its centre, if it differs in density by 1 gm./cm.^{3} from the surrounding rocks. This will be superimposed on a normal background of 980 gal., and so the effect of the structure is to change gravity by 1 in 1,000,000 only. Gravity meters must be sensitive to changes of this order, and they represent the finest work of instrument designers, all precautions being taken to eliminate unwanted effects due to temperature changes, etc. Many instruments claim to detect changes of 1 part in 10,000,000 or better.

In practice some station in the area is selected as a datum station, and by a series of observations with gravity meters the difference in gravity between the various field stations and the datum station is obtained. The

total measured difference, however, is not all attributable to the subterranean geology, many other effects contributing to the observed values. These must be estimated and subtracted from the observations, and there are three corrections to be applied. They are usually called : (*a*) the normal correction, (*b*) the topographical correction, and (*c*) the correction due to level differences.

It has already been pointed out that gravity varies continuously from the equator to the poles and, if the field station is to be north or south of the datum station, part of the measured difference is due to this cause. Formulæ are available which allow the gravity change to be calculated. It varies most rapidly in latitude 45°, and here a displacement of 4000 ft. to the north (or south) gives a gravity change of 1 milligal.

As far as the topography is concerned, surface elevations above the station correspond to excess densities, and depressions below the level of the station to density deficiencies. Thus they make a contribution to the measured value in exactly the same way as a hidden density difference. In all cases the topography tends to reduce the measured value, and this correction is always positive. Irregularities close to the station have little effect, but large features at great distances may be important.

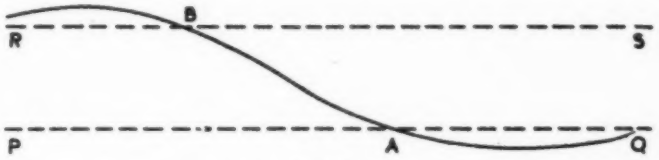

FIG. 13.

THE BOUGUER CORRECTION.

The correction for height can be divided into two parts : the free air correction and the Bouguer correction. The former depends on the inverse square law, gravity decreasing with increasing distance from the earth's centre. Over the range of levels on the earth's surface, the decrease with height is constant, and equal to 0·094 milligal per foot. The accuracy, with which levelling must be carried out, will thus depend on the accuracy of the gravity meter employed in the survey. If *B*, Fig. 13, is the field station and *A* the datum station, when the observations are corrected for topography the values at *A* are reduced to the value which would have been observed if the earth's surface had been *PQ*. Similarly, the value at *B* is reduced to the surface *RS*. Thus, the attracting earth for *B* is greater than the attracting earth for *A*, the difference being due to the layer of rock between the two horizontal planes. This layer increases the attraction at *B*, but is not considered at *A*. The value at *B* must be reduced by the effect of this layer, a correction which depends only on the density of the rock and its thickness. This correction is known as Bouguer's correction.

The space change in the residual values, remaining when these corrections have been applied, arise entirely from the effect of the local geology, and there are two main methods of representing the results. On maps,

gravity values are known at a number of points, the value at the datum station being taken as an arbitrary zero. From these values, lines of equal gravity are drawn in the same way that contours are constructed from a series of spot levels. Such lines are known as isogams, and they form closed curves surrounding regions of gravity high or gravity low. When the observations are made along a traverse, a gravity profile can be constructed. Here the gravity values are plotted against position, and a smooth curve, showing the variation of gravity along the traverse, drawn through the observations.

Torsion-Balancing Prospecting.

The use of the Eötvös Torsion Balance is for the indirect investigation of gravity anomalies, and it measures the gravity gradient and a quantity, the horizontal directing tendency, which depends on the curvatures of the level surface. In this simple description of the principles of prospecting, the latter quantity will not be considered. The unit of gravity gradient is the gal. per centimetre. This unit is extremely large, and a smaller one, the Eötvös Unit (E.U.), is employed, 10^9 E.U. making 1 gal. per centimetre. The torsion balance is somewhat slow in operation, modern instruments taking about 1½ hours to measure up a station completely. This compares unfavourably with the 10–15 minutes of some forms of gravity meter, but it will be seen later the two types of instrument are supplementary, and not alternatives. Modern torsion balances are now automatically recording, and when once the station has been set up, it can be left for the period necessary to take the sequence of readings. As to sensitivity, experience has shown that there is a practical limit dictated by outside factors. As a result, the torsion balance is designed to measure gradients to about the nearest Eötvös Unit.

As in the case of gravity meters, the torsion balance responds to extraneous effects in addition to those arising from buried density differences, and again a number of corrections have to be applied to obtain the residual values. The corrections are : (*a*) the normal correction and (*b*) the correction for topography. As before, the former takes into account the normal increase of gravity from the equator to the poles, and in the northern hemisphere the gradient is equal to 8·2 Sin 2λ E.U. directed towards the north, where λ is the latitude. In the southern hemisphere the same formula applies, but the direction is towards the south.

The correction for topography is usually the most important correction, since surface irregularities near to the balance have a pronounced effect. The effect depends on two factors : the surface geometry, which can be obtained by levelling, and the density of the surface rocks. Since the near features have the greatest influence at the balance, within a circle of about 200 ft. radius about the station, levels are taken to the nearest 0·01 ft. At increasing distance the necessary levelling becomes rougher, and between 200 ft. and 1000 ft. from the station contours at 5 ft. intervals are used in the calculations, while outside the 1000-ft. circle contours at 50-ft. intervals are sufficient. These three regions are usually known as the terrain region (0–200 ft.), the topographical region (200–1000 ft.), and the cartographical region (greater than 2000 ft.). From the levels, or the contours, the gravity gradient produced by the surface features at the

observation station can be obtained using well-established formulæ, either by direct calculation or by graphical methods. The importance of the correction can be appreciated from the fact that a slope of 1 degree, with a surface density of 1·8 gm./cm.^{3}, will produce a gradient acting up the slope of 13 E.U. Of these, 9 E.U. arise from the ground within the first 10 ft. of the balance. For this reason, the ground in the immediate vicinity of the instrument is levelled and the sites must be selected with care. Large gradient corrections arise if the stations are placed on a hillside, but for stations on a ridge, or at the bottom of a valley, the corrections are small, since the effects of deficiencies (or excesses) of mass on each side tend to balance out. In addition to these two main corrections, special features near the balance, such as trees, buildings, cuttings, embankments, etc., are also considered. In general, it is more convenient to consider the

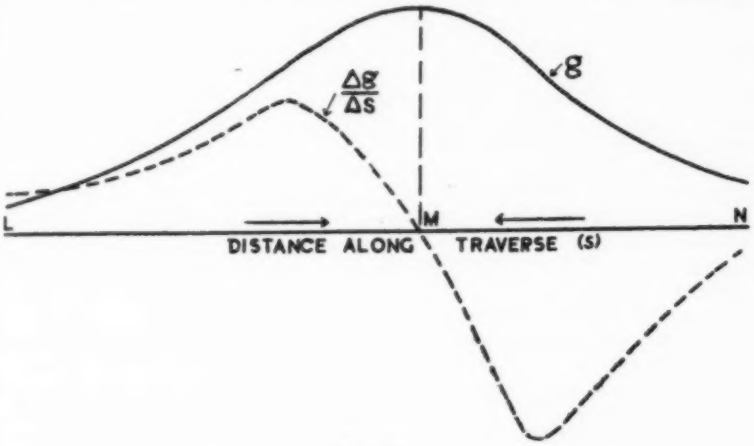

FIG. 14.

RELATION BETWEEN GRAVITY AND GRADIENTS.

two last named features independently instead of including them in the correction for topography.

To represent the gravity gradients on maps, an arrow is drawn of length equal to the magnitude of the gradient on some suitable scale. The direction of the arrow gives the direction in which gravity is increasing most rapidly. The gradient is a vector quantity, and can be resolved into components, or compounded with other gradients acting at the same point, by the same laws that are used to resolve and compound forces. Obviously at right angles to the direction of the gradient there can be no component of the gradient—*i.e.*, gravity does not change in a direction perpendicular to the arrow. This must be the direction of an isogam and, in general, isogams can be drawn from the gradients using this property.

Gravity gradient profiles can also be constructed if a series of observations are made along a traverse. In this case the total gradient is not plotted, but the component of the gradient along the traverse is employed—*i.e.*,

the values plotted show the rate at which gravity is changing along the traverse. In this it is conventional to represent a reversal of direction as a change of sign. Thus in Fig. 14 the positive gradients between L and M represent gradients pointing to the right, and the negative values in the interval MN gradients pointing to the left. There is a simple relation between the gravity anomaly and the gradient, the latter giving the slope of the former (Fig. 14). Further, by integrating the area under the gradient curve, the gravity anomaly can be obtained. Thus, theoretically, the same information can be obtained from both the gravity meter and the torsion balance.

Interpretation of Results.

A qualitative interpretation of a gravitational survey can be obtained immediately by an inspection of the isogams or gradients. The isogams enclose the regions of gravity high or gravity low, while the gradients, indicating the direction of maximum gravity change, point towards the regions of high gravity values and away from the low values. As has already been indicated, gravity highs can be explained by dense rocks approaching the surface, while regions of low gravity values are due to light rocks replacing dense rocks near the surface. If, as is usual, further information is required concerning the shape, size, depth, etc., of the geological feature responsible for the measurements, then calculations must be employed. For certain simple features, such as dykes, horizontal blocks (which might be formed at a fault), etc., the depth and excess mass can be determined directly from the measurements. If the ratio of the thickness of dyke, or block, to its depth is not too small, then this thickness and the density difference can be determined.

In general, the calculation of the gravity anomaly due to a body of any shape is cumbersome and cannot be represented by a useful formula. Thus the quantitative interpretation becomes a system of trial and error in which the experience of the geophysicist plays an important part. A tentative solution for the structure is assumed, and its gravitational effects are calculated and compared with the measurements. Depending on the difference between the two, the assumed structure is modified and its effect recalculated, and this process is repeated until satisfactory agreement is obtained between calculated and measured values. To reduce the time occupied in this process, graphical methods have been developed for the calculation of the effects of irregular bodies and, in some cases, the effects can be measured by using suitable models. Certain principles are used which assist materially in the process. The shape of the anomaly is controlled only by the shape of the structure, the horizontal scale of the anomaly—*i.e.*, its surface extent is controlled by the depth of the feature, while the magnitude of the gradients or gravity values depends on the density difference. Thus a certain feature at a given depth will produce a definite gravity anomaly at the surface. If the depth and dimensions of the feature are doubled, then the anomaly will be spread out over twice the distance on the surface. The magnitude of the gravity gradients remain unchanged by this scale modification, but the gravity values are doubled. Again, changing the density difference by a given factor alters both gradient values and gravity values by the same factor.

These effects are well illustrated by a buried sphere, of radius r, with its centre at a depth equal to its diameter. For unit excess density, the maximum gravity anomaly is given by $\Delta g = 1/3\pi rG$, where G is a constant ($20/3 \times 10^{-8}$ c.g.s. units). Thus, as the sphere increases both in size and depth, the anomaly increases in magnitude, and it becomes more readily detected by a gravity meter. At shallow depths its effects are small and negligible, and this conforms with the statement that surface irregularities near the meter have a small effect. The maximum gradient produced by the sphere is 30 E.U., no matter what its depth, and this maximum always occurs at a distance from the point on the surface immediately above the centre equal to half the depth of the centre. In this case the sphere

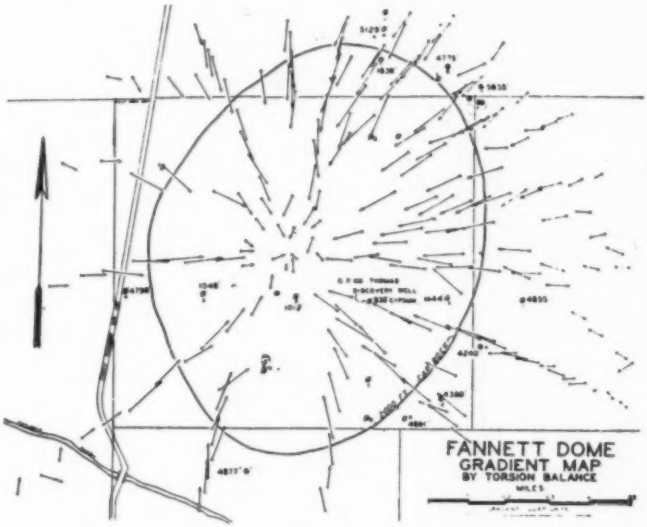

FIG. 15.

GRAVITY GRADIENTS OVER THE FANNET SALT DOME.

is equally detectable at all depths. Thus surface irregularities near the balance have a pronounced effect. For small, shallow features the gravity meter is useless, but the torsion balance can be employed successfully.

An excellent example of a torsion balance survey is the one over the Fannet Dome [7] in Jefferson County, Texas (Fig. 15), the dome being a vertical-sided narrow stock. This dome was originally discovered by seismic methods in 1925, and the torsion balance survey carried out subsequently. It will be seen that all the gradients point to the dome over which there is a gravity high. The cause of this high is the dense cap-rock, for, in general, the salt has a smaller density than the surrounding rocks. As a result, in shallow domes the effect of the cap-rock outweighs the effect of the salt; in deep-seated domes the effect of the salt predominates and a gravity low is usually obtained.

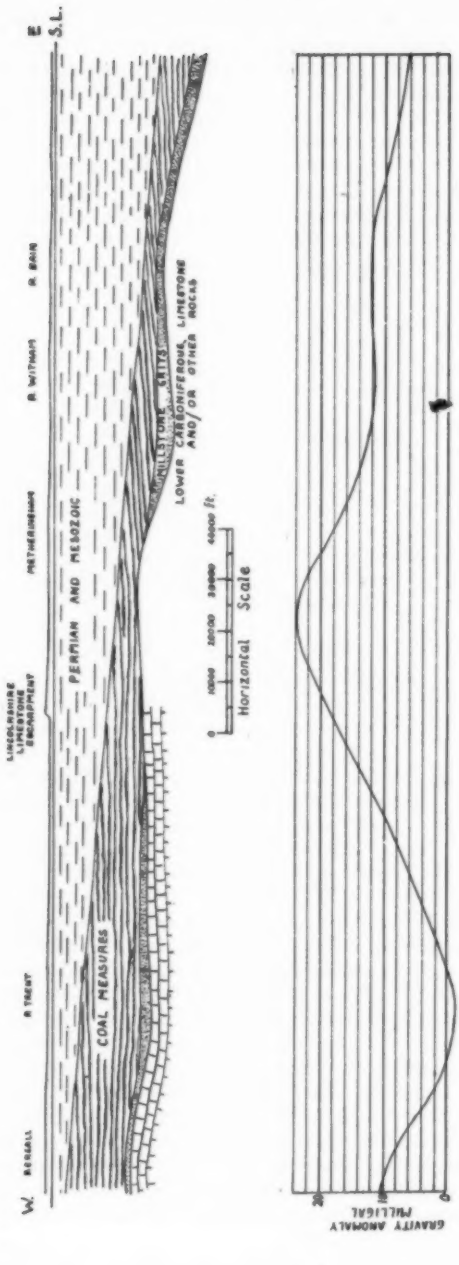

FIG. 16.

GRAVITY SURVEY OVER DERBYSHIRE, NOTTINGHAMSHIRE AND LINCOLNSHIRE.

In the search for oil in England by the D'Arcy Exploration Co., Ltd., a subsidiary of the Anglo-Iranian Oil Co., Ltd., geophysical methods have been employed to detect structures beneath unconformities or alluvial covers. The results of some of their work are shown in Fig. 16, which represents a gravity profile along a traverse of about 40 miles across Nottinghamshire and Lincolnshire.[9] These results have not been obtained directly from gravity meter observations, but have been deduced from a set of torsion-balance stations. The results of some of the torsion-balance work were subsequently confirmed by observations with an Ising gravity meter, and also by pendulum observations at a small number of stations. Over the traverse there is a variation of 26 milligals, with a major maximum near the centre and a smaller ill-defined one farther to the east. These maxima imply an excess of matter immediately below them, and one possible qualitative interpretation is indicated in the geological section, where the gravity highs are explained by anticlines in the Lower Carboniferous rocks. It is possible, however, that they are due to the rise of an older rock massif against which the Carboniferous beds thin out.

Limitations of Gravitational Methods.

One essential condition which must be satisfied is that the structure examined must possess considerable vertical relief, since flat-lying or gently dipping boundaries produce negligible gravitational effects. It should be noted that this latter type of structure is most favourable for the seismic method. With the gravity meter, one limiting factor is the instrument sensitivity, which with the best modern instruments is 0·1 milligal. Thus an anomaly of 2–3 milligal can be examined in reasonable detail, although the presence of a smaller anomaly could be detected. Reference to the buried sphere, which produces 1 milligal, demonstrates that quite pronounced geological features must be available for examination by the method. In short, the gravity meter is suitable for the investigation of large deep-seated structures. On the other hand, the Eötvös Torsion Balance, with which the sensitivity is not a limiting factor, may be employed for shallower bodies which will give a pronounced and measurable gradient, although the magnitude of the gravity value is small.

The smallest gradient of 1 E.U. which can be measured is fixed by the correction for topography. The latter cannot be obtained with very great accuracy, and in rugged country a condition is ultimately reached in which the correction uncertainty masks the effects of the buried geology. The limiting surface conditions obviously depend on the magnitude of the gravity anomaly anticipated for the feature; the larger the gravitational effects, the more rugged the surface may be before the limiting condition is reached. The topography is of minor importance with the gravity meter, since the instrument is insensitive to small nearby features. As, however, it is suitable for large deep-seated bodies, it readily detects the density changes necessary to produce the isostatic compensation for mountains, etc., and over a large surveyed area changes arising from this cause are difficult to assess.

The interpretation of a gravity anomaly in terms of density changes is rarely unique. Even in the simple case of a buried sphere, an analysis shows that only the depth and total excess mass can be determined, the

size of the sphere cannot be obtained without additional information—*i.e.*, the density difference. The same drawback applies to other simple features, such as a dyke or horizontal block. Here the results can only be interpreted as a sheet of a certain mass excess per unit area, but again the density difference allows the thickness to be determined. In the more general case the interpretation is even more uncertain. If it is found that an anomaly can be accounted for by a feature at a certain depth and excess density, then it can be equally well explained by a deeper feature of greater horizontal extent but smaller density difference. Thus it is apparent that other data are required, such as the depth of the boundary at some point, the density excess of the feature, etc.

Results of Gravitational Surveys.

The value of the gravitational method was demonstrated quite clearly by events in the Gulf Coast region of the U.S.A. Sawtelle's data show that from 1902 to 1923 saltdome discoveries averaged little over one per year, but since the introduction of geophysical methods the rate of discovery has been much higher. In the first few years after their introduction the torsion balance, supplemented by refraction prospecting, scored many successes. The prominent low-density salt cores, surrounded by denser sediments in an area of low relief, frequently provided especially favourable conditions for the application of the torsion balance. Eby and Clark[7] give a series of examples of the gravity pictures of Gulf Coast domes, and it is interesting to note the gravity minima over deep-seated domes and the maxima over the shallow domes caused by the relatively high-density cap-rock. The Moss Bluff Dome shows the combined effect for such a feature at an intermediate depth, being characterized by minimum gradients around the dome and large gradients above it.

Gravity surveys on a regional basis can often give a useful, although not complete, picture of the geology of an area. The regional gravity anomalies are due to major warping of the basement, by which is implied either igneous and metamorphic rocks, or a series of well-consolidated beds, lying on the crystalline rocks, the basement being cloaked by less dense sediments. Thus the regional framework of central Southern Oklahoma, and the adjacent parts of Texas, as displayed in a gravity map, agrees well with, and even goes beyond, the known geological data.[13]

Electrical Coring.

Of the many electrical methods of geophysical prospecting, the only one of any importance in oil prospecting is the method of electrical coring developed by Schlumberger. Originally, it consisted of making a survey of the resistivities * of the rocks penetrated by a bore-hole, but this is now supplemented by measurements which reveal changes in the porosity of the rocks. Combining these two sets of observations allows important information to be obtained concerning the nature of the various rocks.

* The resistivity of a material is defined as the resistance of a piece of the material of unit cross section and unit length, the current flowing in the direction of the length. It is measured in ohm. centimetres, ohm. metres or ohm. feet, depending on the unit of length adopted.

Most minerals, except a few base metal sulphides and oxides, are non-conductors of electricity, and the electrical conductivity of rocks in nature depends entirely on the solutions present. The two factors which control the resistivity of a rock are the amount of solutions present and the conducting properties of the solutions, the latter increasing as the salt content increases. Both these factors vary through a wide range; the amount of solutions present varying from less than 1 per cent. by volume for a

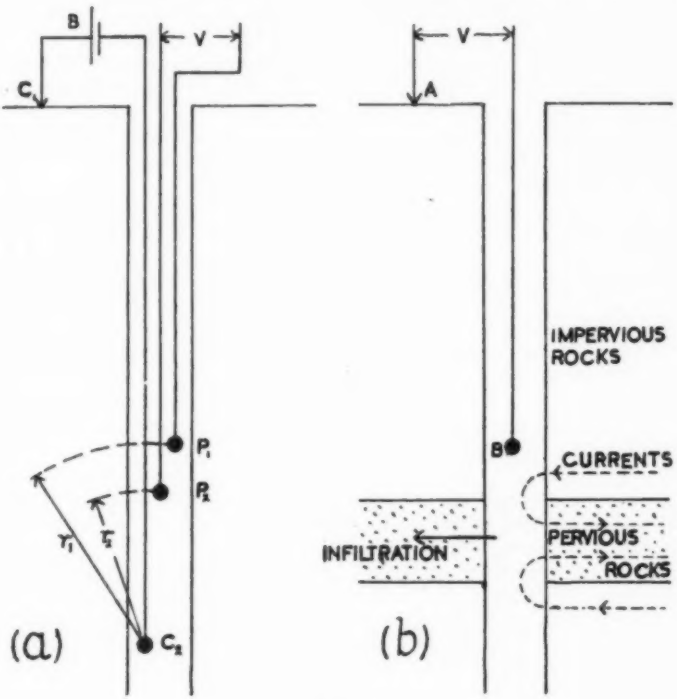

FIG. 17.

THE PRINCIPLES OF (*a*) RESISTIVITY MEASUREMENTS IN BOREHOLES, AND (*b*) PERMEABILITY MEASUREMENTS.

compact crystalline rock up to about 50 per cent. for loose sand, while the resistivity of the solutions changes from some 300,000 ohm. cm. for fresh waters down to 20 ohm. cm. for saturated solutions. Accordingly, rock resistivities are not characteristics of the rock itself, but characteristics of the conditions under which it occurs. Generally speaking, crystalline rocks possess the highest resistivity values, consolidated sediments fill an intermediate range, while recent unconsolidated sediments have the lowest values, the whole covering a range from 10,000,000 ohm. cm. down to 200 ohm. cm. It should be noted that the three groups indicated above

overlap in their resistivity ranges. The presence of oil, replacing the saline solutions, within a rock will reduce considerably its conducting properties, an oil-saturated sand having in general a high resistivity.

Only one of the methods of measuring rock resistivities in boreholes will be described here : the three-electrode method, which is the one normally employed. The observations can only be made in an uncased borehole which is filled with a loose mud. Three contacts, or electrodes, P_1, P_2, C_2 (Fig. 17), are lowered at the end of a suitably strengthened triple-cored cable into the mud, under the weight of a heavy lead sinker. So that depth measurements, given by the length of cable, shall not be in error due to slack in the cable, measurements are only taken as the system is raised from the bottom. A current I is passed between the lowest electrode C_2 and a fixed surface electrode C_1, while the voltage V set up between P_1 and P_2 is measured by a potentiometer. If r_1, r_2 are the distances C_2P_1, C_2P_2, respectively, then when C_1P_1 is large compared with r_1 and r_2, the resistivity ρ of the ground is given by

$$\rho = 4\pi \frac{r_1 r_2}{r_1 - r_2} \frac{V}{I}.$$

The rocks which contribute the major part of this measured value are those lying between and to the sides of the line P_1P_2, and hence the measured value can be taken as a close approximation to the resistivity of the rocks through which the electrodes P_1, P_2 are passing. By maintaining the current constant, since r_1 and r_2 are fixed, a continuous record of V gives a measure of the variation of ρ. The presence of the mud modifies the values measured, but the changes in the measured resistivity are still significant.

An example of the results of electrical coring is shown in Fig. 18. It depicts the variation in the resistivity in two wells, $\frac{3}{4}$ mile apart, in the Oklahoma City Pool,[9] and the sections show the type of results to be expected in the case of regular sedimentation. It should be noted that in the correlation of the two wells the absolute value is not the only feature to be considered, for the nature of the resistivity profile is also instructive. The zones with a regular profile correspond to homogeneous shales, and often clays give similar uniform and constant values. In fact, clays and shales are considered to be among the best electrical markers on account of their uniformity. On the other hand, the saw-toothed profiles corresponding to limestone and sandy shales are not such good markers. If the geological column at one well is known, and the lithological changes can be associated with resistivity variations, the structure can be obtained from the electrical measurements. Well-marked contacts have been traced for tens of miles in this way.

Even if the precise significance of the resistivities is not known, considerable information can be obtained from the electrical diagrams alone. If, however, an attempt is made to identify the rocks from even outstanding resistivity values, serious errors are likely to arise. Thus a high resistivity value may correspond to an oil-sand, a fresh-water sand, gypsum, or some limestone. By introducing the second parameter, the porosity, some of these formations may be distinguished, particularly if the probability of occurrence of certain beds can be eliminated geologically. The porosity

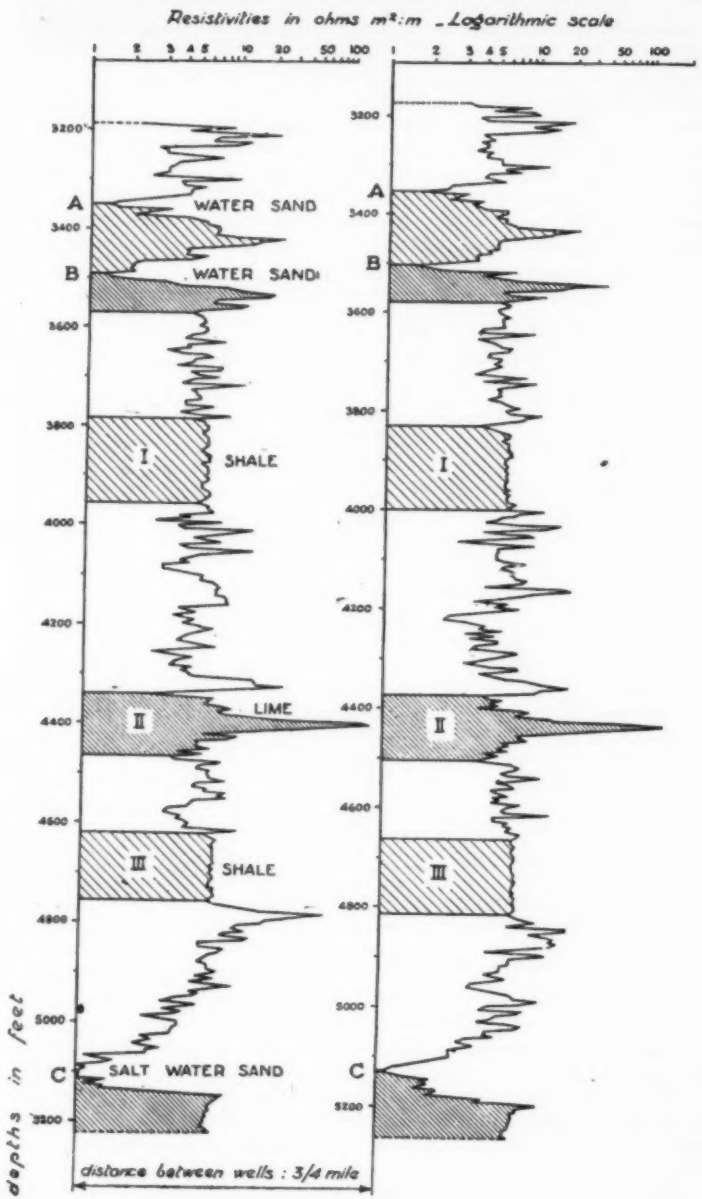

FIG. 18.

RESISTIVITY MEASUREMENTS IN BOREHOLES.

is examined qualitatively by the natural potential differences found in boreholes. They arise from two causes, *electro-infiltration* and *electro-osmosis*.

If the interstices of a dielectric, such as sand, are filled with a salt solution, and a pressure set up so that the liquid flows through the medium, then electric currents also flow, usually in the direction of the pressure drop. Voltage differences arise from the flow of the electric currents. This is the phenomenon of *electro-infiltration*. The magnitude of the voltage drop is proportional to the resistivity of the electrolyte and to the quantity of liquid filtering through the medium, and is therefore closely

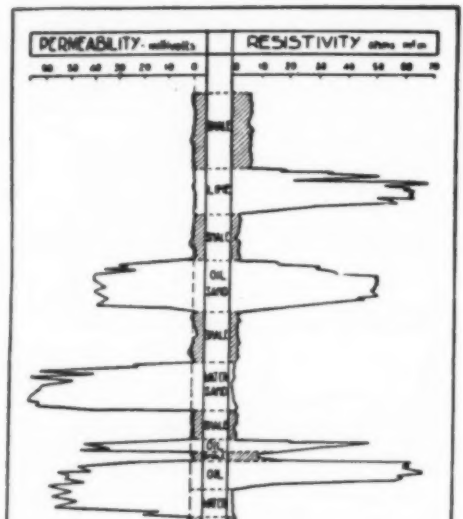

FIG. 19.

THE INTERPRETATION OF RESISTIVITY AND PERMEABILITY LOGS.

related to the permeability of the rock. In general, the pressure in any one formation differs from that arising from the head of mud, and usually there is an infiltration of the electrolyte of the mud into the rocks. Currents will be set up as shown in Fig. 17(*b*), and with an electrode at the surface and the other moving down the hole, a negative voltage will be recorded as the moving electrode passes the pervious formation. The phenomenon is well pronounced, voltage differences between 50 and 100 millivolts having been recorded. Special non-polarizing electrodes must be employed for this type of measurement.

When two liquids of different salt content are brought into contact, there is set up between them a voltage difference. In weak solutions the

voltage difference is a function of the ratio of the electrical conductivities. Again, in general, the salinity of the solution, present in the mud, differs from that contained within the rocks, and a voltage arises from this cause. In most cases it is found that the two effects are additive, giving an increased measured difference. The main result is that the voltage is not a direct measure of permeability. By changing the pressure head of mud, or the salinity, the two effects could be separated, but in practice this is unnecessary. Large voltage differences are found to correspond to permeable media, and low values are associated with impervious strata. It should be noted that these effects are also observed when oil is the liquid within the rocks, as this is usually contaminated by a small amount of salt solution.

The interpretation of the combined resistivity and natural potential logs [10] is typified by Fig. 19. Here the first bed has a low resistivity and permeability, and corresponds to a shale. This is followed by a high-resistivity bed having a low-permeability and, in this case, indicates a limestone. In addition to other beds of limestone, there are oil-sands characterized by high resistivities and high permeabilities, and water-sands with low resistivities and high permeabilities. It should be noted that the combination of high resistivity and low permeability would be given by other beds—*e.g.*, gypsum—as well as limestone and the combination high resistivity, high porosity by a fresh-water sand. Although it would appear, at first sight, that these measurements are more definite and more readily interpreted than many geophysical surveys, the conditions are not always as simple as these examples suggest, and in some cases no interpretation of the observations has been found possible.

Another process closely allied to electrical logging is the newer method of radioactive or gamma-ray logging. When wells are cased, resistivity and self-potential measurements are useless, due to the effective shielding of the metal casing. To some extent the radioactive method can be used instead, since the radioactivity can penetrate through several strings of casings. Most rocks contain very small amounts of radioactive minerals—*i.e.*, uranium, actinium, thorium, and their disintegration products—and the occurrence of the weakly active elements, potassium and rubidium, is widespread. During their disintegration three types of rays are emitted and, of these, the gamma rays, extremely short-wave X-rays, can be detected by suitably sensitive equipment lowered down the borehole. The radioactive minerals in sedimentary rocks varies considerably, limestones and sandstones being nearly inactive, while shales contain the most, the important feature being the possibility of differentiating between sands and shales.

Results of Electrical Logging.

While the ability of electrical logging to locate oil, gas, water-sands, and other features which are of prime importance in the individual wells, is generally recognized to be of great value, from the broader view of geophysical surveying its main utility lies in its application to electrical correlation. Numerous examples of correlation by electrical logging have been recorded, not only for individual fields, but also for much wider areas. Within fields, it has facilitated the unravelling of structural complexities, and it has shown frequently that faults are far more numerous than has

been suggested by other means (*e.g.*, Surakhany). In this connection it has proved most useful in exploring the flanks of saltdomes. Lenticularity and wedging are also revealed.

As an example of correlation over long distances by means of electrical logs, sections described by Deussen and Owen [14] may be noted. In these sections, correlation is based on the electrical characteristics of the formations, in addition to their foraminiferal content, and by these means several formations have been traced through from deep underground to outcrop. The presence of a non-outcropping wedge of Oligocene marine shale is also well displayed. Thus, in its ability to correlate formations over long distances under certain conditions, the cautious application of electrical logging provides an additional aid in the location of all-important stratigraphic traps.

Magnetic Prospecting.

It is well known that one magnet, placed in the vicinity of another, will experience a force of attraction or repulsion depending on their relative

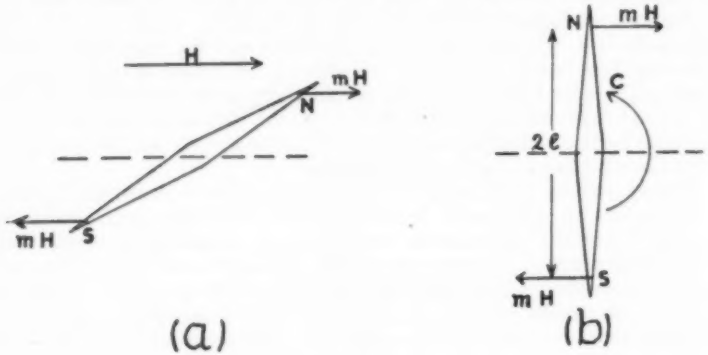

Fig. 20.

THE MEASUREMENT OF MAGNETIC FIELD STRENGTH.

positions. The region around a magnet in which these forces are apparent is called the magnetic field of the magnet. To measure the strength of the magnetic field at any point, it is convenient to consider the force acting on unit magnetic pole instead of a magnet, the magnetic intensity, or field strength, being defined as the force on unit pole placed at the point in question. Since the intensity is essentially a force, it has both magnitude and direction, and can be resolved into components, or compounded with other fields, using the same rules for the resolving and compounding of mechanical forces. The unit of magnetic field strength is the oersted, which is equivalent to a force of 1 dyne on unit pole. In geophysics, however, the older term of gauss is usually retained. For geophysical prospecting, the gauss is inconveniently large, and a smaller one is universally adopted called the gamma (γ) where an intensity of 100,000γ is equal to 1 gauss.

Although for purposes of definition it is convenient to consider the force

or unit pole, all the necessary information concerning the field can be obtained from a freely suspended magnet. In a field of intensity H, the forces acting on the two poles constitute a couple tending to rotate it into the direction of the field (Fig. 20). Thus, when the magnet is in equilibrium, under the magnetic forces only, the line joining the poles gives the direction of the field. To rotate and hold the magnet at right angles to its equilibrium position requires a couple to counterbalance the magnetic couple of $2mlH$ (Fig. 20(b)), where m is the pole strength and $2l$ their separation. The product $2ml$ is the moment of the magnet and is a constant, and so for a

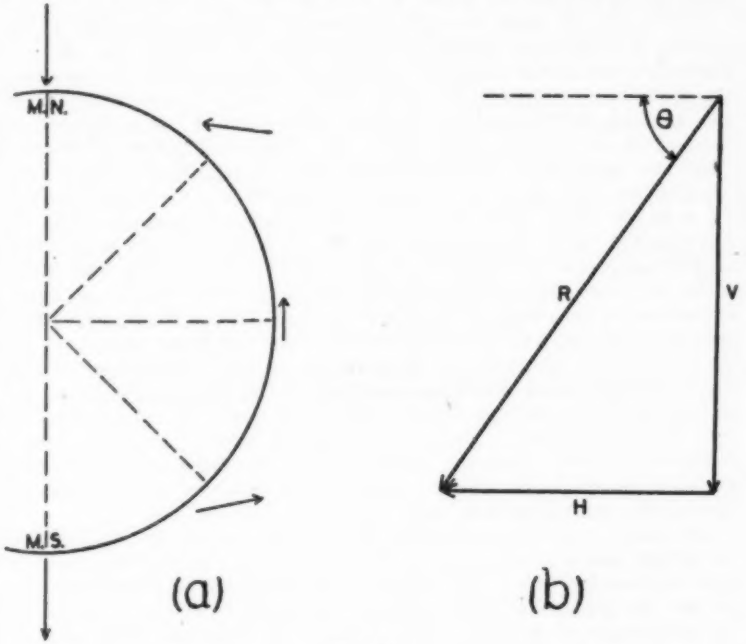

FIG. 21.
(a) THE MAGNETIC FIELD OF THE EARTH, (b) THE MAGNETIC ELEMENTS.

given magnet the couple required to maintain the magnet perpendicular to the field is a measure of the field strength.

The magnetic field of the earth, which forms a background for all geomagnetic surveys, can be represented approximately by that of a small magnet of large moment at the earth's centre, with its south pole pointing to the magnetic north pole of the earth. This does not coincide with the geographical pole, so that a magnet does not point true north, the difference, which varies over the earth, being defined as the declination. At the magnetic pole the intensity is vertical (Fig. 21(a)), and at the magnetic equator it is horizontal. At other points the intensity R is inclined to the horizontal by an angle known as the dip θ, and in the northern hemi-

sphere the N pole of a magnetic dips downwards. The total intensity R is usually resolved into a vertical component V and a horizontal component H (Fig. 21*b*). The vertical field varies from a maximum of 0·6 gauss at the poles to zero at the equator, while H changes from zero (at the poles) to 0·3 gauss (at the equator). This is only an approximation to the earth's field; it is far more irregular than this simple picture, and the normal variation cannot be represented accurately by simple formulæ. Superimposed on this steady field, there are fairly regular daily variations in the intensity of 20–30γ, with occasional magnetic storms which may cause changes of 1000γ in a few hours.

Most materials, when placed in a magnetic field, become magnets, the moment M of the induced magnet depending on the field R, the volume of the body v and on the material. If R is the internal field in the specimen, the moment is given by $M = RvK$, where K is a constant depending on the material, and is called the magnetic susceptibility. It is the moment induced in unit volume when placed in a magnetizing field of 1 gauss. Only two minerals of any importance have outstanding magnetic susceptibilities, and these are magnetite ($K = 97{,}000 \cdot 10^{-6}$) and ilmenite ($K = 30{,}000 \cdot 10^{-6}$); the majority of other minerals have susceptibilities less than $400 \cdot 10^{-6}$. The susceptibility of a rock depends, to a great extent, on the magnetite and ilmenite content, with the result that sedimentary rocks, as a rule, have low values less than $400 \cdot 10^{-6}$. There are certain exceptions to this, such as the magnetic shales of the Rand, which have been so useful in tracing the extension of the auriferous conglomerates. As igneous rocks usually have a high magnetite and ilmenite content, they are frequently found with high susceptibilities of the order of $3000 \cdot 10^{-6}$ or more, and it is this type of rock which can be examined most successfully by magnetic methods. These susceptibilities lead to an induced magnetism of the rocks under the action of the earth's field, but in many cases the rocks possess a permanent magnetism, the direction of which does not necessarily coincide with the direction of the induced type.

The main principles involved in the method can best be illustrated by the simple case of a body lying parallel to the earth's field so that the upper end becomes a S pole. The length of the body will be considered great so that the lower N pole will contribute a negligible effect at the surface. In the absence of the body, both vertical and horizontal fields would be constant as indicated by the broken curves (Fig. 22) and by the arrows H and V. To this simple field must be added the attraction between unit pole at the surface and the S pole of the body, a force which always points towards S and varies inversely as the square of the distance. At A this extra intensity will be negligible, and the normal values of V and H will be observed. At B, C, and D, however, it will make an appreciable contribution, and its vertical component will increase up to D when the vertical field will be a maximum giving the curve KLM. The horizontal component of the additive force at first increases, but due to the changing direction it falls away and at D it is zero; to the north of D the horizontal component opposes the earth's field. Thus the change in horizontal intensity will follow the curve RTW.

The pole distribution produced by the interaction of the earth's field, and the body is rarely as simple as this, and the resulting anomaly is more

complex. The distribution depends on a number of factors, including the shape and size of the body, the magnitude of the earth's inducing field, and the susceptibility involved. The relation of the body and the direction of the earth's total field is a most important factor. A dyke, for example, with its strike length in the magnetic meridian would have poles induced only on its upper surface, while if it is perpendicular to the magnetic meridian there will be, in addition, poles induced on the walls. Although

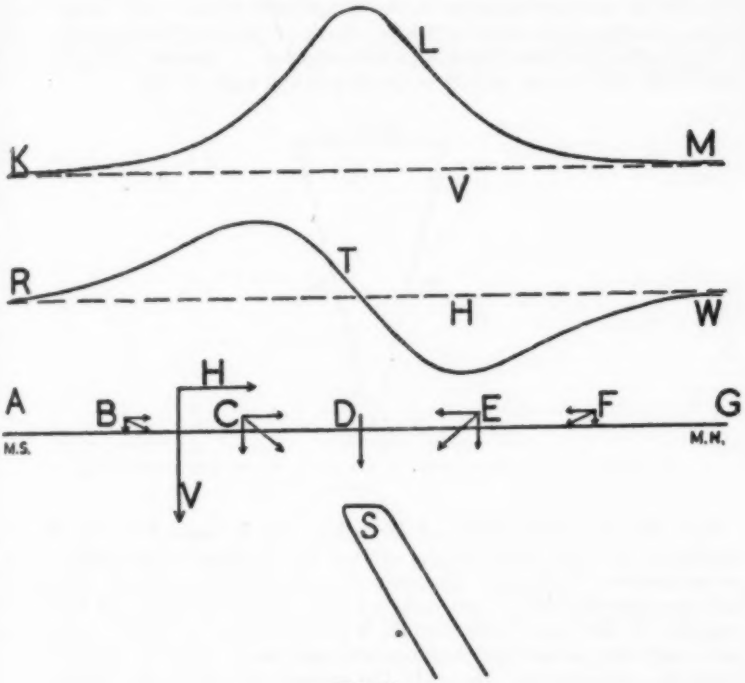

FIG. 22.

MODIFICATION OF THE EARTH'S MAGNETIC FIELD BY A BODY OF HIGH SUSCEPTIBILITY.

in the two cases the dimensions, susceptibility and total field may be identical, the nature of the anomalies may differ considerably. Again, the same body at different latitudes will yield differing results. Thus a sphere at the magnetic pole would give a maximum in the vertical field immediately over its centre, while at the magnetic equator the vertical field would show a smaller maximum to the south of the sphere, and an equal minimum to the north. Immediately above its centre there would be no anomalous vertical field.

To measure the anomalies instruments known as magnetic variometers are employed, and these measure differences between the fields at various

points. The most useful instrument is the vertical variometer which measures changes in the vertical field, but horizontal variometers are also available. The former, however, are more reliable and, in general, yield results which are more readily interpreted. This arises from the fact that a considerable anomaly can be present without causing any appreciable change in the magnitude of the horizontal field; but only in its direction as shown in Fig. 23. Here H is the normal field, ΔH the anomaly and these combine to give a resultant field H' equal in magnitude to H. Horizontal variometers measure changes in the magnitude of the total horizontal force. Another instrument which can be employed for this type of prospecting is the Hotchkiss Superdip, which responds to changes in the earth's total field, and to some extent to changes in the angle of dip.

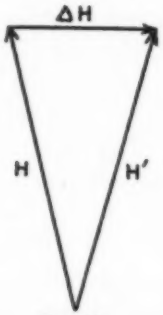

FIG. 23.

A LARGE ANOMALY MAY LEAVE THE MAGNITUDE OF THE HORIZONTAL COMPONENT UNCHANGED.

As in the case of gravitational surveying, certain corrections have to be applied to the field observations so that the residual values apply only to the geology of the area. The main corrections are the normal correction and the correction for diurnal variation and magnetic storms. It has been pointed out that no simple formula is available for the earth's magnetic field, and the normal correction is obtained from regional maps of the magnetic components. To apply the second correction, the changes in the earth's field with time can be obtained from an observatory, if one is sufficiently close, or one instrument in a fixed position is used to observe the changes. In surveys over large anomalies and in the absence of large magnetic storms, it is sufficient to return at intervals to a fixed station and estimate the time change during the intervals between repeated observations.

Interpretation and Limitations of the Magnetic Methods.

The representation of results is most conveniently done by constructing lines of equal magnetic component, or by magnetic profiles which show the variation of the measured component along a traverse. A qualitative interpretation is usually possible by inspection, taking into account the direction of the earth's field. A more detailed interpretation can be made involving tedious computation. It can be shown that there is a simple

relation between the magnetic anomaly and the gravitational anomaly produced by the same body. Accordingly, many of the remarks on the interpretation of gravitational surveys are applicable here and, in particular, the same ambiguities arise. On the whole the interpretation of a magnetic anomaly is more difficult than a gravitational anomaly, for the latter is a characteristic of the body, while the former arise from the interaction of the external field and the body.

Application of the Magnetic Methods.

Although the magnetic method has been used extensively, mainly on account of its cheapness, it has only a limited application to oil prospecting.

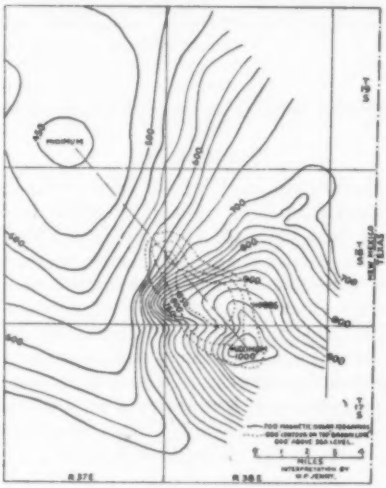

FIG. 24.

MAGNETIC SURVEY AT HOBBS FIELD, LEA COUNTY, NEW MEXICO.

The search here becomes mainly a search for basement uplifts which may arch the superincumbent sediments into a suitable oil-trap. It should be noted that such a movement is not necessarily associated with an oil structure, since this implies that the movement has taken place after the sedimentary deposition. Frequently, magnetic anomalies appear to be due to changes in the susceptibility of the basement itself and have no relation to structure. Serpentine plugs, which have an appreciable susceptibility, have been found useful for the location of certain faulted zones, as in Texas.

Examples of the results of magnetic prospecting are given in Figs. 24 and 25. The former, over Hobbs Field, Lea County, New Mexico, gives an anomaly in the vertical field of the earth produced by a basement uplift,[11] the basement being at a depth of approximately 10,000 feet. The structure is revealed magnetically by a maximum vertical field in the south-east and a minimum in the north-west. It will be seen that the maximum does not coincide with the crest in the anticline shown by the

contours of the "Brown Lime" horizon, the displacement being due to the inclination of the inducing field. The latter shows a magnetic profile over a serpentine plug associated with a fault in the Yoast field, Bastrop County, Texas.[12]

FIG. 25.

MAGNETIC PROFILE OVER YOAST FIELD, BASTROP COUNTY, TEXAS.

CONCLUSIONS.

It will be appreciated that in this brief description the main principles only have been considered, and matters relating to instruments, field technique, etc., have been omitted. Nevertheless a thorough understanding of these principles should enable the reader to form some judgement of the utility of the various methods and the problems in which they may be usefully employed. Once more it must be emphasized that the presence, or otherwise, of oil in the structures delineated by the geophysical methods cannot be inferred from any of the observations, even in the case of electrical coring, where the physical properties of the oil may enter into the measurements. The interpretation can be used only to guide the selection of the most promising sites for boreholes and in this capacity it has been found of great use, particularly in the oil fields of America.

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Illustrations.

Certain of the figures illustrating this paper have been reproduced by the kind permission of the American Association of Petroleum Geologists, the American Institute of Mechanical Engineers, the Oxford University Press and the Editors of "Nature."

THE INSTITUTE OF PETROLEUM.

A MEETING of the Institute of Petroleum was held at Manson House, 26, Portland Place, London, W.1, on Friday, 28th April, 1944, when the President, PROFESSOR F. H. GARNER, was in the Chair.

The following paper was presented by Dr. J. McGarva Bruckshaw: "Geophysical Methods Applied to Oil Prospecting." (See pp. 271–310.)

THE AUTHOR, before reading his paper, said that he thought he should start with a word of explanation which, in some respects, was an apology for some of the deficiencies which he was sure would be fairly prominent in this paper. It was not written for the purpose of being delivered to a meeting of this kind. In fact, he had been asked to write a chapter covering the methods of geophysical prospecting that could be read by the layman and to form part of a handbook covering the whole aspect of fuel technology. As such, he had very great difficulty in presenting the information he wished to impart in the limited space allotted for the purpose. Now his task was even more difficult, because he had to compress an already abbreviated Section of a Handbook into an account which he could deliver in something of the order of 50 minutes or so.

DISCUSSION.

THE PRESIDENT said that the author had said that this paper was a chapter from a book which was being prepared by the Institute on "Modern Petroleum Technology," and the main purpose of this book was to give information of various branches of the industry to people engaged in the industry and he thought that it would be agreed that this is a very useful summary of the work on geophysical prospecting. One point he would like to ask the author about was his references in the paper to Sawtelle's data, which probably exclusively referred to the American data. It would be useful if the author would give the full reference in his bibliography.

THE AUTHOR said that he was under the impression that he had given the reference, but if he had omitted to do so it would be well worth while adding that to the list of references at the end. Sawtelle [1] had published one review of the application of geophysics and the achievements that have been obtained, and he felt it would be a good thing to place that at the disposal of people who had a general interest in the method and its application.

MR. J. C. TEMPLETON said that he would like to take this opportunity of congratulating the author on the lucid and eloquent manner in which he had described a very complex subject, and would like also to emphasise some of the outstanding points on which the author had touched. Geophysics alone did not provide a complete picture of the sub-surface conditions, nevertheless, it was of considerable assistance in prospecting for oil and was specially valuable to the geologist. The problem, as they knew, was essentially geological. By means of physical measurements, however, additional data were obtained wherewith to elucidate and determine the underground conditions. As the author had stated, this method was for the most part indirect and did not locate oil, as such, but assisted in locating the conditions favourable to the accumulation of oil. There was probably one exception to the indirect approach which deserved mention at this time. It was not strictly geophysical, but in large measure it came within the purview of the geophysicist and was likewise of great interest to the geologist. The object of the geo-chemical method was to determine the percentage of hydrocarbon gases, peculiar to petroleum, present in the sub-surface, particularly the sub-soil. At the present time we had not sufficient data on which to assess the full value of this method, but it opened up a new field of investigation, which had some promise of success.

There was another point on which he would like to touch, namely, the limitations of the various methods, which had been described very clearly by the author. Some oil technologists expected very little from geophysics, others expected far too much. Frequently they oscillated between these two extremes. Probably a little too much emphasis was placed on structural determination. He thought a clearer picture was

[1] *A.A.P.G., Bull.*, **20**, June 1936, 726–735.

presented if it was remembered that they were endeavouring to determine the configuration and position of interfaces in the sub-surface, and that such interfaces were not necessarily structural. He referred to the interfaces between rock formations or rock bodies having different physical properties. These might be unconformities. As the geologist was well aware, the physical properties might vary quite rapidly within a single formation, in which case it was not possible to elucidate the structure by purely physical means.

The physical measurements as such were reasonably accurate and, from a purely physical standpoint, the determination of the sub-surface structure might seem straightforward. The determination of the shape or configuration of the concealed rock masses, or the geological interpretation of the measured data and the assessment of the conditions deduced, in relation to the accumulation and concentration of petroleum—the ultimate objective—was, however, not so simple.

One hundred per cent homogeneity was seldom realized in the sub-surface formations or rock masses. This and other physical irregularities frequently set the limit to the useful application of any particular geophysical method. It behoved one, therefore, to consider fully the known geological facts, at the outset in selecting the most suitable geophysical method or methods, and finally in determining the significance and value of the physical data.

Therefore, he would stress the importance, in future developments, of greater co-operation between physicist and geologist. Only by the geologist acquiring more knowledge of physics and the technique of geophysical measurements and the physicist realizing something of the geological complexities, of which the geologist was all too well aware, should we attain the maximum success in the application of geophysics. Today we were not only concerned with structural traps for oil, but also with stratigraphic traps. By knowing something of the difficulties and limitations, the oil technologist would better understand and appreciate the scope and value of geophysical prospecting methods.

THE AUTHOR said that he would like to thank Mr. Templeton for his very kind remarks and he would also like to associate himself with the last part of his speech because he found it very difficult to alternate between the magician who could produce anything out of the hat or the charlatan who could not do anything right. As far as geo-chemical methods were concerned, he was not very familiar with the latest developments but it had always seemed to him that one was still going to have the same difficulty because the presence of suitable hydrocarbons in the subsoil was no criterion of the amount of oil which might be within the structure; although it might indicate the presence of a certain amount of oil it would not indicate the quantity, and so the whole problem was by no means solved by certain observations by the application of geo-chemical methods themselves.

MR. TEMPLETON agreed that the geo-chemical method was not complete in itself, but it might be of great assistance.

THE AUTHOR replied that that was so.

MR. TEMPLETON said that when we had determined that hydrocarbons—gaseous or liquid—were present in a structure, the oil possibilities were enhanced very considerably. Without that knowledge we might drill into a structure with completely negative results.

MR. CAMPBELL HUNTER asked the author what he regarded as the most satisfactory method of approach for structures say in rocky mountainous country? He was referring particularly to the foothills in Alberta where he understood they had tried geophysical methods but he did not think with any great success.

THE AUTHOR said that he did not know very much about the work in Alberta but the most promising method there appeared to be either the refraction seismic method or the reflection seismic method. A certain amount of correction had to be applied for irregularities at the surface but these could be applied with sufficient accuracy not to mask the significance of the results in terms of geology. In all probability the surfaces would be far too erratic for the application of the gravitational method, and the magnetic method required certain features to be present before it could be used with any great success. Therefore, one was more or less forced back on to the seismic method, but without further details of what had been done and of the problem to be solved, he was afraid he was not in a position to make any definite comment on this particular problem.

WATER FOR OILFIELDS DEVELOPMENT.

By G. W. Halse (Member).

Before drilling for oil can be commenced in undeveloped countries, one of the first problems which must be solved is the provision of a water supply.

The following notes show how water was found by Trinidad Petroleum Development Co., Ltd., British Controlled Oilfields, Ltd., and Ecuador Oilfields, Ltd., respectively :—

Trinidad Petroleum Development Co., Ltd., Trinidad.

Palo Seco Well No. 1 commenced drilling in Trinidad on 5th February, 1926. Water for drilling was obtained from the Erin River, a small muddy stream, in which an earth dam was constructed and from which the water was pumped 1350 feet. This and other local river supplies were used for drilling the first forty wells. This water supply had the disadvantages that it carried a lot of clay matter in suspension during the rainy seasons, and that the rivers generally cease to flow completely during dry seasons.

To obviate both these drawbacks the Cyrnos dam was constructed at the end of 1928 (Fig. 1). Records taken in the vicinity over twenty years showed a variation in the annual rainfall from 49 to 73 inches. Effective precipitation was assumed to be 25 inches or 41 per cent. of the average total of 61 inches per year, the balance being allowed for as loss by filtration and evaporation. When measurements were being taken in the Northern Range preparatory to building the Quare dam, which now supplies much of the water to Port-of-Spain, San Fernando, etc., it was found that, with a rainfall of 141 inches in the Quare Valley in 1922, 43 per cent. of the rain passed as run-off over the weir set up for measuring it, the remaining 57 per cent. being lost by evaporation and filtration (Trinidad and Tobago Council Paper No. 48 of 1924). The accompanying map (Fig. 2) shows the truly remarkable variations of rainfall within very short distances in Trinidad. It is only 50 miles across the island from the north coast to the south coast.

The catchment area for the Cyrnos dam is 50 acres. It is entirely wooded or covered with cocoa plantations, so that soil erosion, which would silt up the reservoir, is at a minimum. The height of the dam is 17 feet. When full it contains nearly 30 million Imperial gallons. The assumed effective rainfall of 25 inches on 50 acres in a year would accumulate 28 million gallons. From this must be deducted evaporation from the surface of the water itself, together with a certain amount of leakage. In the Quare Valley it is stated in the Council Paper quoted above that small-scale measurements indicated that an evaporation rate of 1 inch per week from reservoir surfaces should be assumed.

Field requirements at the time at Palo Seco with four drilling strings in operation were estimated at 200,000 Imperial gallons per day (5700 barrels)

or 73 million gallons per year. Thus it is seen that not only was the total rainfall inadequate to fill the reservoir in a year, but that when full, allowing for evaporation, it contained barely sufficient water to last for four months.

The frequent anxiety caused by the small reserve of water in the dry weather was found to be justified during the first few months of 1931,

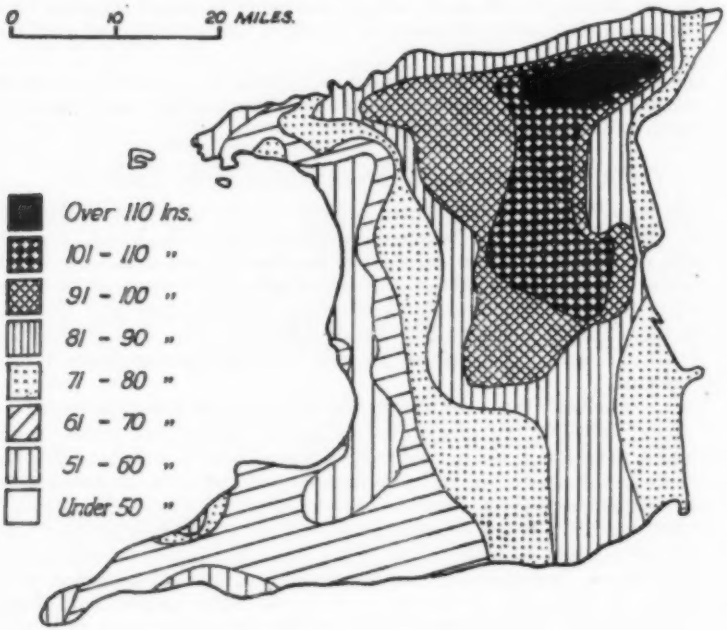

FIG. 2.

RAINFALL DISTRIBUTION IN TRINIDAD.

when there was an exceptionally prolonged dry season. The Cyrnos reservoir became exhausted, and the only water available consisted of some small pools still remaining in the rivers. By moving pumps to one pool after another, a limited and precarious supply was obtained. Drilling was disorganized and several stoppages occurred until the rains commenced.

The inadequate size of the catchment area would normally be overcome by finding an alternative site, but the local topography, position of roads, houses, and well locations were such as to preclude the use of suitable sites

which were found. The situation was generally saved by the fact that the local rivers do not dry up immediately the rains cease, but continue to flow for from one to two months. Pumps were therefore set up permanently in four of the local rivers, not only to supplement the insufficient rainfall and fill the reservoir during the rains, but also to continue to supply water to it into the dry season as long as the rivers lasted. The drawback still remained, however, that a four-months' dry period, after the rivers had dried up, was the longest which the water supply would last.

On the 19th July, 1932, the first Schlumberger Electric Survey of an oil-well in Trinidad was made. This was at T.P.D. Palo Seco Well No. 126. In addition to oil and salt water, the diagram showed what the Schlumberger Engineers interpreted as fresh-water sands at shallow depth.

Although drilling shallow wells for water had previously been discussed, it was not actually carried out until after the important evidence of the Schlumberger device was obtained. Then the drilling of shallow " pup " water wells was commenced from the same derricks as oil wells in which the Schlumberger Survey for oil had also indicated shallow fresh water. These pup wells start about 4 feet from the main well at surface, and are drilled without moving anything except the rotary table (Fig. 3). They commence with an initial deviation of 3°, the rotary table being canted this amount. Sufficient weight is kept on the bit during drilling to ensure deviation away from the main well near the surface. Their depth is usually about 600 feet. In the soft sands and shales penetrated, dipping at 15–30°, a considerable number of directional surveys have shown a general tendency to deviate fairly straight up dip. For instance, in one T.P.D. field fifteen directional surveys to depths up to 6400 feet gave over-all deviations on bearings from 100–180°, the straight-up dip direction bearing 160°. Even wells with an initial deviation down dip have been found to curve round to an up-dip direction.

The result of drilling these water wells (Fig. 4) was that a supply of fresh water adequate for the expanding needs of the company was quickly established, and the previous frequent anxiety as to whether the water would last until the next rains was entirely eliminated.

The sands supplying the water are all monoclinal, and outcrop within 1500 feet or so of their respective wells. Rain falling on these outcrops fills up the sands with water which is tapped in the wells. Under these conditions any sand would fill with water, but in the area under consideration there are two geological horizons which are particularly suitable. At Palo Seco and Coora the Morne L'Enfer sands (sometimes called Upper Moruga) of Upper Miocene age supply the water. This formation in general is sandy, but is characterized by a considerable admixture of thin bedded argillaceous matter. It does, however, contain sands fairly free of clay, particularly in its upper horizons, which make good water sands.

At Los Bajos, the " Porcellanite Beds," of Pliocene age, contain excellent water sands (Fig. 5). Their name is due to their containing lignites which, when sufficiently near the surface to be reached by atmospheric oxygen, have ignited spontaneously and have baked the adjoining clays. In 1938

one of these localities was smouldering at Cedros, due to a bed of lignite 9 feet below the surface. The overlying clay was burnt to the characteristic bright red colour. These " Burnt Clays " or " Porcellanites " which occur at intervals over a distance of 15 miles are of great economic importance in south-west Trinidad, and are extensively quarried, since they provide the only locally available supply of road metal. In both cases the water sands are continuous or sheet sands, as contrasted with the Forest and Cruse oil-bearing sands of Middle and Lower Miocene age which are highly lenticular.

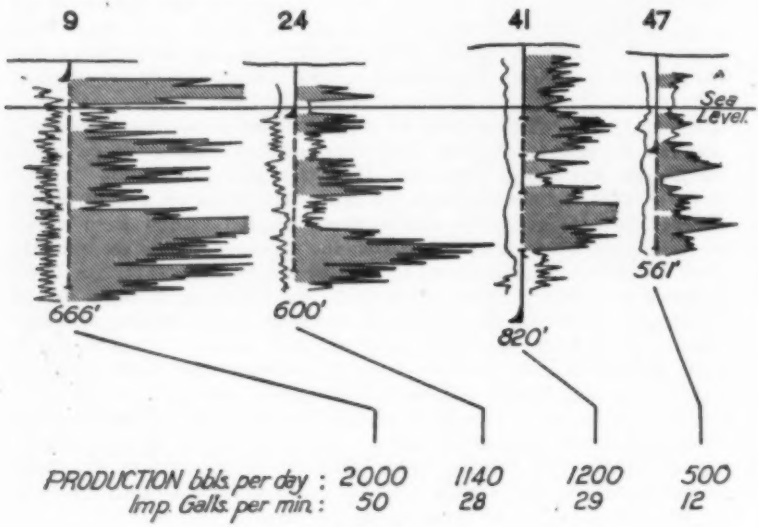

FIG. 6.

SCHLUMBERGER DIAGRAMS, LOS BAJOS.

The accompanying Schlumberger diagrams show typical water sands of the Porcellanite (Fig. 6) and of the Morne L'Enfer beds (Fig. 7). The output and chemical analyses of the waters are added in each case. The casing in practically all wells is a $5\frac{3}{4}$ inch combination string with $\frac{3}{8}$ inch perforations, fifteen holes per foot. None of the wells are gravel packed. The water is produced by gas lift using surplus almost dry gas from high-pressure separators. This gas is delivered through reducing valves to the wells at pressures varying from 60 to 165 lbs. per square inch. The input string is either 1 inch or $1\frac{1}{4}$ inch diameter, and from 175 to 420 feet deep. The water flows through the annulus between this and 3 inch or four inch pipe which is set not less than 50 feet deeper than the input pipe. The total production of water by this means is about 14,000 barrels (490,000 Imperial gallons) per day from some eleven wells. In a few cases the output of water cannot be increased without fine sand entering the well, but in some cases there is little doubt that a considerable increase would be possible.

The water is quite suitable for general purposes, but is rather hard. Treatment to prevent the formation of hard scale is necessary before it can be used in boilers or water-jackets. The addition of 1 lb. of Quebracho to each 11,000 Imperial gallons of feed-water is found to be adequate for softening and reducing scale to a satisfactory degree.

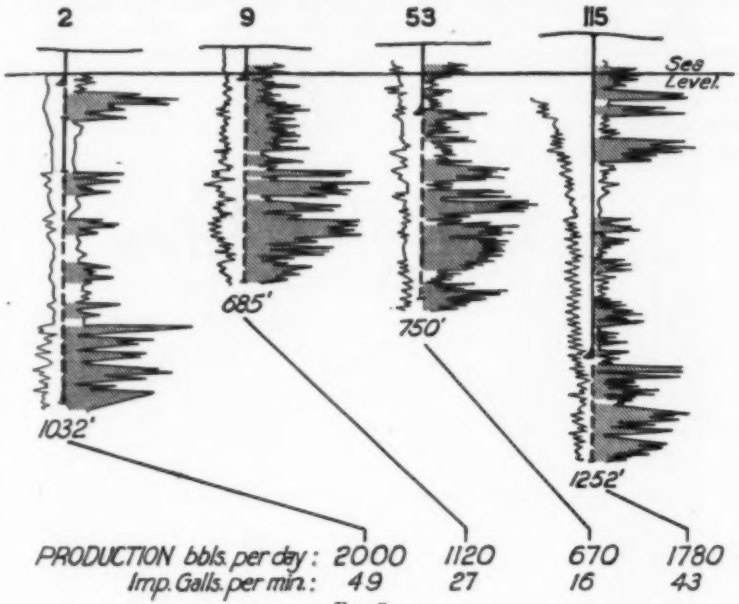

FIG. 7.

SCHLUMBERGER DIAGRAMS, COORA.

BRITISH CONTROLLED OILFIELDS, LTD., VENEZUELA.

The El Mene oilfield of B.C.O., Ltd., is situated in semi-arid country 40 miles east of the town of Maracaibo. When drilling commenced in 1919 there was only one inhabitant at El Mene, as compared with some 4000 people now. The only water supply was from a hand-dug well or two which gave a little brackish water, and from small ponds made by excavation and banking.

Figures taken over eighteen years show that the rainfall at El Mene averages 40½ inches per year. The annual totals in inches are :—

Year.	Rainfall.	Year.	Rainfall.	Year.	Rainfall.
1925	34·7	1931	44·6	1937	31·3
1926	36·5	1932	46·4	1938	55·1
1927	51·2	1933	54·3	1939	28·7
1928	38·6	1934	44·6	1940	41·6
1929	29·4	1935	40·0	1941	27·9
1930	38·3	1936	43·7	1942	42·7

The average monthly distribution of this rain is shown in the accompanying curve (Fig. 8).

In 1919 the River Maticora formed the only suitable supply of water for oilfield work. Although running water ceases in the lower reaches of this river a couple of months or so after the commencement of the dry season, some pools of water remain throughout the year. As these pools communicate with gravels beneath the river banks, a moderate supply of water is obtainable from them after the river ceases to flow.

In order to commence drilling at El Mene, a pump-station was set up at the river Maticora, and water was delivered 4 miles through a 2-inch line for the drilling of El Mene Exploitation Well No. 1, which was completed in September 1920.

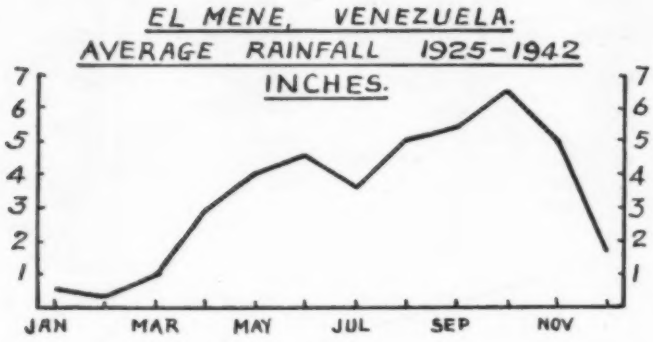

FIG. 8.

EL MENE RAINFALL CURVE.

Regular development drilling commenced in 1923. To obtain additional water in a convenient situation two water wells 450 feet deep were drilled near No. 1 well, and they produced steadily some 200 barrels of water per day each.

During the years 1923–1927 there was usually a shortage of water in March, owing to the drying up of the River Maticora after three or four months of dry season. In this period ten more water-wells between 400 and 500 feet deep were drilled within the oilfield, and occasionally an oil-well would be stopped at shallow depth in order to utilize temporarily the fresh water passed through. In April 1924, after seven dry months, it was found that the output of the shallow water wells fell off considerably. A falling off was noticed late in the following year also.

In 1925 a 6 inch oil line for delivering oil to the lake shore was completed, and the previous 4 inch oil line was used for pumping water from Lake Maracaibo, 35 miles to El Mene. The main supply, however, was still from the Maticora River (Fig. 9).

From 1925 to 1928 inclusive forty-seven wells were completed in El Mene each year. Drilling was entirely by the Cable Tool System, and wells rarely exceeded 1000 feet in depth, so sufficient steam was supplied by

FIG. 1.
CYRNOS DAM.

[*To face p.* 318.

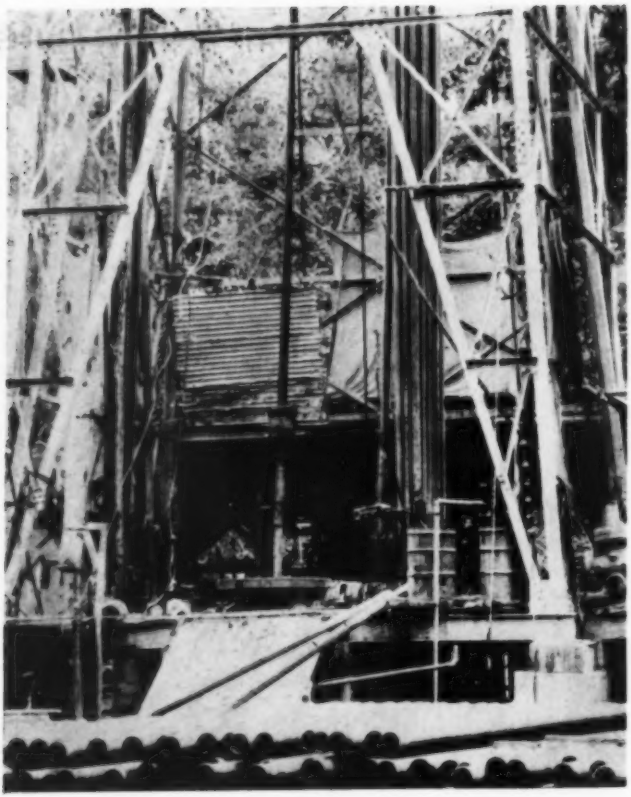

FIG. 3.

PUP WELL DRILLING.

FIG. 4.

COMPLETED WATER AND OIL WELLS.

FIG. 5.

MEASURING WEIR FOR WATER WELL.

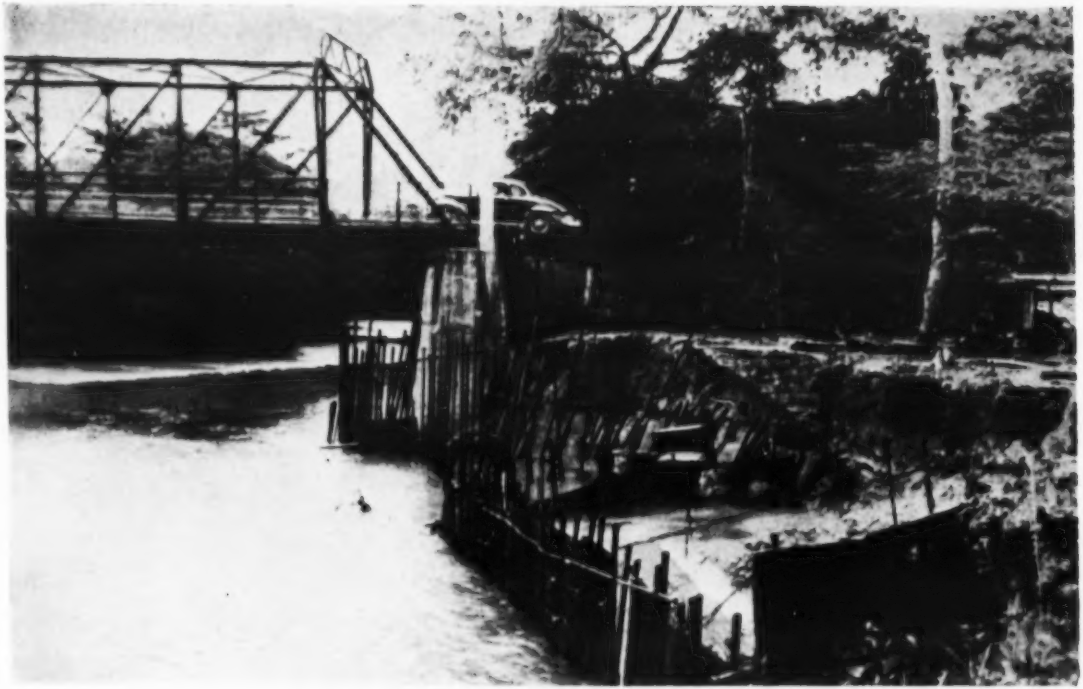

FIG. 9.
RIVER MATICORA.

FIG. 9.
RIVER MATICORA.

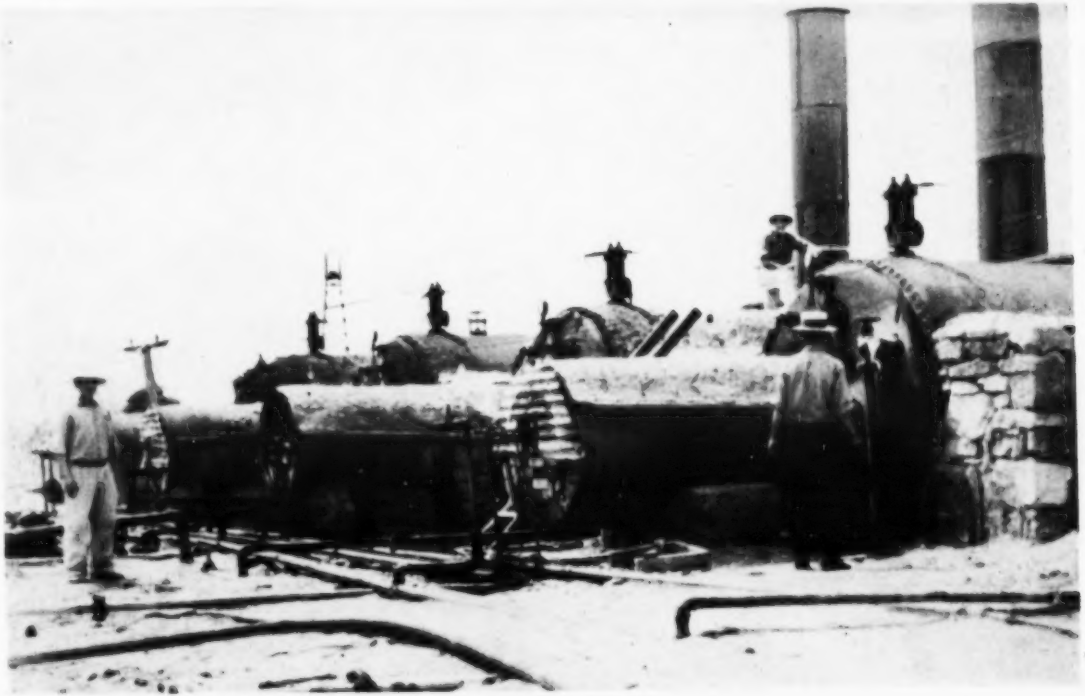

FIG. 13.
BATTERY OF CORNISH BOILERS.

FIG. 14.

SEA WATER SUCTION LINES.

FIG. 14.

SEA WATER SUCTION LINES.

FIG. 15.

SEA WATER SETTLING TANKS.

FIG. 16.
HEAT EXCHANGER.

one boiler for each well. Water consumption therefore was very low as compared with rotary drilling requirements.

In 1928 rotary drilling with the latest-type rigs then available was standardized for exploratory drilling. In addition, a recovery plant for extracting light ends from rich gas was erected at El Mene. This extra equipment called for a greatly increased water supply. Furthermore, the mud which was always present in the water when the river was in flood could no longer be tolerated. Various pits, 5 feet × 5 feet × 25 feet deep, were sunk beside the Maticora river, but 50–150 feet away from the bank. The object of these was not only to increase the supply of water, but also to obtain clear water when the river was in flood and muddy. The intervening gravels and sand formed a natural filter, and clean water was obtained at an initial rate of 75,000 gallons (2100 barrels) per day per pit, but the supply fell off through gradual clogging of the communicating beds with clay.

It was not until the Llanitos well was completed in 1929 that the water supply problem was really satisfactorily solved. This well was drilled for oil, which it failed to find, but none the less it turned out to be highly profitable. It is situated 3½ miles east of El Mene on the south side of the fold axis, and was drilled by cable tools. This system allowed the collection of samples of water struck in the well as follows :—

Depth, ft.	Salinity, Parts per 100,000.	Geological Formation.
1375	8	Upper Miocene
2620	960	Miocene
2938	1179	Miocene
3130	1190	Eocene ?
3324	23	Eocene ?

The deep-seated fresh water, below salt water, indicates the structural complexity of the region. Furthermore, the temperature of the fresh water from 1375 feet is 120° F. To have reached this temperature it appears that this fresh water must have come from a depth of not less than 4000 feet. It flows naturally at the rate of 1300 barrels per day, and has a slightly sulphurous smell as it emerges, but this quickly disappears, and cannot be detected where the water is used.

Compressors and pumps were installed at Llanitos in 1929, and the well has given some 8000 barrels of water per day ever since by air-lift. 4-inch tubing is set at 200 feet, and air is introduced outside this, between it and the 12½-inch casing. The kick-off pressure is 125 lb. per square inch, and the running pressure 60 lb. per square inch. The only interruptions in nearly fourteen years of production have been of a few hours' duration, when it is necessary to change the tubing once a year because the bottom 80 feet becomes furred up by the deposition of scale, and so restricts the output of water. Total production of water during this period has been some 41 million barrels, or about 8½ million cubic yards, and there is no apparent reason why it could not go on producing at this rate indefinitely.

In 1930 the demand for water rose to over 10,000 barrels per day. Analyses of the water from the La Ceiba well showed it to be unsuitable

FIG. 16. HEAT EXCHANGER.

for boilers, so two water wells were drilled to 400 feet depth at Mono Bluff, between El Mene and Llanitos. Together they yielded over 5000 barrels per day of excellent water by air-lift from sands of the La Puerta formation.

The dominating geological feature of this region is the Barranca Basin (Figs. 10 and 11), a saucer-shaped synclinal basin 16 miles in diameter. This rigid unit has resisted compression, but older beds outcropping from

FIG. 10.
BARRANCA BASIN.

beneath it on the north, east, and south sides have been sharply folded and crushed.

The Llanitos well is on the north-east rim of the basin where the main east-north-east fold axis of the region passes tangentially from the rim. At the southern circumference of the basin Vega Oscura Well No. 2, completed in 1936, found at 4300 feet depth a flow of 3000 barrels per day of water of salinity 5 parts per 100,000 and temperature 147° F. This came from rocks of Oligocene age. La Ceiba No. 1 well, down the slope of the basin, 6 miles from its northern edge, was drilled to 4648 feet depth

in 1925 and 1926. It struck an estimated flow of 4000 barrels per day of "hot flowing fresh water" at between 1600 and 2300 feet and salt water at 4638 feet. This fresh water was reported to be unsuitable for use in boilers.

The results of these wells show that a very large supply of bacteriologically innocuous water is obtainable in this region, though in some cases high mineral content precludes it from being classified as good potable water. Furthermore, artesian flow of considerable magnitude was found. This is no doubt because the La Puerta formation covers most of the Barranca Basin, and the mottled clays which it contains form an efficient impervious cover to hold in the water, while the hills and mountains south-east of the Basin afford ample opportunity for accumulating the head necessary for artesian flow.

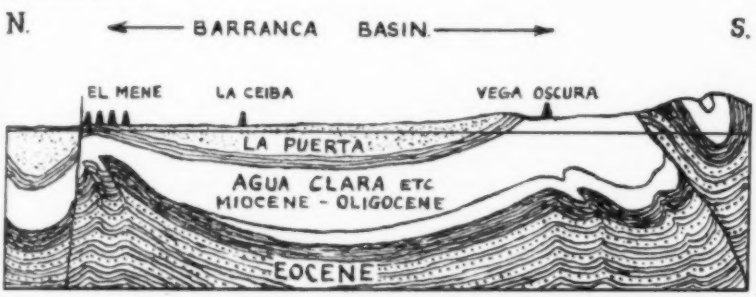

FIG. 11.

SECTION, BARRANCA BASIN.

It was at one time thought that the extensive south dipping flank of the Barranca Basin, culminating northwards in the El Mene anticline, had given rise to migration of oil up the flank and accumulation near the crest at El Mene. If this were so, waters now associated with the oil would be expected to be fresh, but they are not; they are salt. Furthermore, the waters in the northern part of the field run about 450 parts of salt per 100,000, whereas those down the flank and more into the fresh water saturated Barranca Basin are more saline—namely, 900 parts per 100,000. This is the reverse of what would be expected had the soil migrated up dip from the basin, and is a strong indication, if not a proof, that the Barranca Basin is not the source of the El Mene oil.

The Llanitos well is situated on the south edge of a complex faulted anticlinal core. The high temperature of the water produced from 1375 feet is suggestive that it may be the same fresh water which occurs at 3324 feet, and which may reach the higher level through a fault channel. The anticlinal core has been mapped in considerable detail, but all geological evidence immediately to the south of the well is concealed by alluvium. There was no specific reason for anticipating a prolific water supply here—in fact, the faulting might well have been thought to have formed a barrier preventing access of water from the Barranca Basin. It may be stated,

therefore, that all the geological evidence available, including that from the Llanitos well itself, would not have enabled the striking of a big supply of fresh water there to have been predicted.

Ecuador Oilfields, Ltd., Ecuador.

The Santa Elena Peninsula, where the only oilfields at present developed in Ecuador are situated, is almost on the Equator, and consists of semi-arid, low-lying country with a very variable rainfall confined to the first four months of the year. Anglo-Ecuadorian Oilfields, Ltd., have kindly furnished the following figures for rainfall at Ancon :—

Rainfall.		Rainfall.		Rainfall.	
Year.	Inches.	Year.	Inches.	Year.	Inches.
1925	40·15	1932	30·10	1938	5·58
1926	26·62	1933	20·70	1939	44·91
1927	3·60	1934	6·70	1940	5·81
1928	2·53	1935	7·55	1941	19·97
1929	16·80	1936	7·46	1942	2·75
1930	3·96	1937	7·20	1943	15·12
1931	2·82				

The annual variation, between 2½ and 45 inches, is seen to be very large. The average rain for the nineteen years is 14·23 inches, and its average distribution is shown on the accompanying curve (Fig. 12).

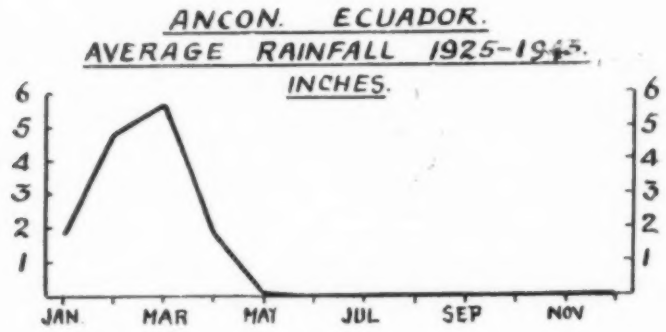

Fig. 12.

ANCON RAINFALL CURVE.

Probably during the period of Inca colonization, which was extensive in this area, and certainly since the time of the Spanish Conquistadores, water supply was obtained exclusively from hand-dug pits and dams. The water in the pits is often brackish and is liable to be polluted from nearby houses. The reservoirs formed by the dams afford a supply which

is variable and precarious. They frequently dry up completely, as may well be understood from the rainfall figures given above.

The value of water reservoirs is greatly enhanced by the unusual climatic conditions of the Santa Elena Peninsula. The Rumboldt Current of cold sea-water from the South Polar region impinges on the Pacific Coast at Santa Elena and greatly reduces the temperature. It also causes the region to be covered with fog or low-lying cloud, which almost entirely excludes sunshine from May to October. The fog is locally known as "Garua." It is a most important factor in reducing evaporation from reservoir surfaces, and results in the water lasting much longer than it would under normal tropical conditions.

As local fresh-water resources are entirely inadequate for oilfield development, and specially for rotary drilling, Anglo-Ecuadorian Oilfields, Ltd., introduced the use of sea water for steam-raising for drilling in 1919. Ecuador Oilfields, Ltd., started a similar practice in 1937.

For this purpose Cornish-type boilers are used. They consist of a shell 22 feet long and 6 feet 6 inches diameter with a single internal flue 3 feet 3 inches diameter (Fig. 13). Every eleven days each boiler is shut down for men to enter and remove the scale, which chips off easily. The amount recovered is from 100 to 150 lb. per boiler. It consists mainly of $CaSO_4$ and $CaCO_3$ with only just over 1 per cent. of salt, yet the sea-water used in the boilers contains over 3 per cent. of salt as compared with about 1 per cent. of other constituents. In other words, the boiler concentrates the lime, etc., some 300 times more than the salt. This shows how effectively blowing down removes the salt : it is done every one or two hours. In practice over a number of years the use of sea-water in these boilers has been found to be quite satisfactory. Perhaps the main disadvantage is that the boilers are not easily portable, since they have to be bricked in so that the flue gases can heat the outer shell after passing through the internal flue.

For withdrawing water from the sea (Fig. 14) a diaphragm-type pump is used, as this can handle sand, which cannot be avoided with suction lines on an exposed coast. This water is delivered into settling tanks (Fig. 15), from which it is pumped to the field. Corrosion of pipe-lines is severe.

While the use of sea-water solves part of the problem of water supply, fresh water is essential for rotary mud and for general purposes. It was found that Schlumberger diagrams could not be taken satisfactorily in wells using mud made with sea-water, because its resistivity was too low. This alone, therefore, is a sufficient reason why fresh water is essential for drilling mud.

Geological conditions in the Peninsula are unfavourable for the accumulation of water in quantity. The surface formation is composed of a thin Recent Shelly sand and beach deposit called the Tablazo, which lies horizontally in patches on folded Oligocene and Eocene beds. The Eocene consists mainly of impervious clays and cherts which cover most of the Peninsula proper. The prospects of water in this region are small because of the thinness of the Tablazo, which connotes lack of volumetric capacity in the possible reservoir beds.

Notwithstanding these conditions, in 1929 Ecuador Oilfields, Ltd.,

drilled some wells 120 feet deep and obtained a supply of fresh water. The wells have been on production ever since, and particulars are as follows :—

Well:	No. 1.	No. 2.	No. 3.	No. 4.
Production, barrels per day .	100	200	100	100
Sp. G. of water at 29° C. .	0·9975	0·9960	0·9965	0·9970
Total solids per 100,000 . .	213·0	81·8	201·0	244·7
Sodium chloride per 100,000 .	128·9	37·5	114·8	152·3
Sulphates at SO_4 per 100,000 .	24·19	10·37	22·20	28·64

(*Analyses by Anglo-Ecuadorian Oilfields, Ltd.*)

The wells are spaced at 600 ft., and the differences in the above analyses indicate that each well enters a separate reservoir. This is quite in accordance with the known geological conditions.

The fresh-water supply is augmented to the extent of 100 to 150 barrels per day per rig by condensing the exhaust steam from mud-pumps and drilling engines. The steam is passed through a simple heat exchanger (Fig. 16), in which it gives up its best to the incoming sea-water for boiler-feed. The condensed steam is collected in a tank for use at the rig.

Apart from being insufficient in quantity, the existing fresh-water supply has the following defects :—

Source.	Remarks.
Shallow drilled wells	Rather high mineral content.
Hand-dug pits	High mineral content and contamination.
Earth reservoirs	Contaminated by animals and dry up completely some years.
Condensation of sea water	Good.

Geological investigation was recently undertaken with the object of finding flat dipping sandstones which would form a reservoir beneath the Tablazo. Such an area was found, and by drilling 6 wells 100 feet deep each a supply of 2000 barrels per day of good water was quickly developed. The lasting powers of this supply are dependent on the degree of porosity of the underlying sandstone and can only be ascertained by trial over an extended period. In the meantime, it is a good indication that the withdrawal of water for the first few months failed to lower the fluid level.

From the foregoing it is seen that the provision of a water supply for drilling is a subject as wide in its scope as it is interesting and important.

OBITUARY.

JOHN GILLESPIE.

Many old friends of Mr. John Gillespie, in the Institute of Petroleum and in the Burmah and Anglo-Iranian Companies, will be very sorry to hear of his death, which occurred on May 27th at the age of 79. Mr. Gillespie, who for over thirty-one years was head of the Burmah Oil Company's Engineering Department, retired in September 1928, and it will interest his friends to read the following extract from the note which appeared in *The Naft* of November, 1928 :—

> " Mr. Gillespie's retirement recalls the early days of the Anglo-Persian Oil Company when, as Consulting Engineer to the Burmah Oil Company in Glasgow, he prepared the first plans for plant in Persia and selected many of the early employees of the Anglo-Persian Oil Company's technical staff. His connection on the engineering side with operations in Persia even ante-dates the present Company, going back to the days of the Concession Syndicate, when he was associated with the late Mr. G. B. Reynolds who, as our readers will recall, subsequently brought in the first oil well at Masjid-i-Sulaiman. Later, on the formation of the Anglo-Persian Company, Mr. Gillespie, in collaboration with Mr. Andrew Campbell, prepared the first plans for the Abadan Refinery, and similarly worked in collaboration with the late Mr. Charles Ritchie in connection with the laying of the original Persian pipe-line."

He was elected a member of the Institute in 1920 and served on Council from 1931 to 1933.

JAMES CUTHILL, O.B.E.

It is with deep regret that we have to record the death of Mr. James Cuthill, Chairman of the Northern Branch. Mr. Cuthill joined the Institute in 1924, and became a Fellow in 1939.

Mr. Cuthill was born at Motherwell, and served his apprenticeship with The Steel Company of Scotland and Duncan Stewart & Co., Ltd., Glasgow, after being educated at Uddingston Grammar School.

He was subsequently with Mirrlees Watson & Co., Ltd., Glasgow, and J. R. Houston & Co., Ltd., Greenock, before returning to the Blochairn works of The Steel Company of Scotland, where he became Chief Engineer and Assistant Works Manager.

In 1921, he joined The Oil Well Engineering Co. of Stockport, as Works Manager, at the time when the changeover from cable tool to rotary drilling was getting into its stride.

In 1939, on the death of Mr. W. L. Mackenzie, he was appointed General Manager of the Company, and in the New Year Honours of 1943 was

awarded the O.B.E. in recognition of his outstanding work in the war effort.

Mr. Cuthill was a man of many interests. He was a Rotarian, Past-President of Stockport Rotary Club; a member of various Youth Committees, National Savings Committee, Air Training Corps, and St. John Ambulance Brigade. He was a man of notable personality and personal achievement.

Throughout the existence of the Northern Branch of the Institute, Mr. Cuthill has taken the keenest interest in its activities and organisation. His loss will be felt keenly by all who knew him.